Application of the conditioned network concept in high frequency power line carrier

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Application of the Conditioned Network concept in High Frequency Power Line Carrier

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Memorandum

All work and ideas recorded in this dissertation are original unless otherwise acknowledged in the text by reference. The work has not been submitted in support of an application for another degree in this university, nor for any degree or diploma at any other institution.

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Abstract

The aim of the research described in this thesis was to investigate the possible use of underground Low Voltage Distribution Networks as a medium for the propagation of high frequency communication and data signals. Although the results and observations presented are based upon work carried out on a typical UK urban underground network, the same principles apply to most European underground Low Voltage Distribution Networks. The work was based around the use of frequencies greater than 1 MHz; these high frequencies provide enough bandwidth for a number of value added services to be offered in addition to the more usual Utility requirements for remote meter reading and load control. The research resulted in the development of an in-line filter element designed to limit the amount of Power Line Carrier noise egress from a distribution network whilst at the same time reducing the amount of high frequency noise entering the network.

The effects of the Electricity Distribution Network on high frequency signals are discussed in some detail. All Power Line Carrier systems must be capable of operating in the presence of noise. Network topology and individual network elements have a significant effect on high frequency signals; a number of topologies are described and the effects of changes in characteristic impedance and discontinuities are discussed.

The results and observations were largely obtained from a Low Voltage Electricity Distribution Network in Kendal, Cumbria. The limited availability of expensive high frequency test equipment resulted in the need to develop unique testing procedures; these are described in full. Sample results from the tests undertaken in Kendal are presented and discussed.

The Conditioned Network concept is outlined and the design rules used to develop the in-line Conditioning Unit highlighted. A mathematical model for the filter element of the Conditioning Unit is developed and compared to empirical results obtained from laboratory experiments.

Glossary of Terms

a.c.	Alternating current
ADSL	Asymmetric Digital Subscriber Line
AF	Audio Frequency
AM	Amplitude Modulation
ASCII	American Standard Code for Information Interchange
BBC	British Broadcasting Corporation
Baud	Number of state changes per second
CALMS	Credit and Load Management System
CALMU	Credit and Load Management Unit
CCITT	Comite Consultatif International Telegraphic et Telephonique
CEGB	Central Electricity Generating Board
CENELEC	Comite Europeene de Normalisation Electrotechnique *(European Committee for Electrotechnical Standardisation)*
CPU	Central Processing Unit
CTCU	Central Teleswitching Control Unit
CU	Conditioning Unit
DAC	Digital to Analogue Converter
d.c.	Direct current
DDC	Distribution Data Collector
ERA	Electricity Research Association
FM	Frequency Modulation
FSK	Frequency Shift Keying
HDLC	High-level Data Link Control
HF	High Frequency
HRC	High Rupturing Capacity

IEC	International Electrotechnical Commission
ISO/OSI	International Standards Organisation / Open Systems Interconnection
kV	Kilovolt
kW	Kilowatt
LEB	London Electricity Board
LMT	Low voltage Master Terminal
LPT	Low voltage Process control Terminal
LV	Low Voltage
MCU	Medium voltage Coupling Unit
MGU	Medium voltage Gateway Unit
MMU	Medium voltage Master Unit
MPU	Medium voltage Process control Unit
MW	Megawatt
OFFER	Office of Electricity Regulation
OFgem	Office of Gas and Electricity Markets
PLC	Power Line Carrier
PPU	Peripheral Processing Unit
REC	Regional Electricity Company
r.f.	Radio frequency
SCR	Silicon Controlled Rectifier
SSB	Single Sideband
VHF	Very High Frequency

Chapter 1: History of the Electricity Supply Industry and PLC

1.1 Introduction

This thesis describes research into Power Line Communications and its associated filters. The research programme was supported by NORWEB plc, a company within the United Utilities group. The work was sponsored by NORWEB, and the experimental programme of work was carried out in the NORWEB area of the UK. The initial brief for the research was broad enough to allow not only an investigation into existing ideas and technologies, but also to develop novel solutions to a long running quest, that of how to reliably increase the amount of information a Low Voltage Electricity Distribution Network could carry. Although sponsored work, the type of equipment best suited to this activity was too expensive to purchase or hire; this resulted in the need to develop novel testing procedures with easily available equipment in order to obtain results vital to the research.

The three primary work areas were as follows:

1) A literature search, in which a detailed investigation into the history and development of power line technology, was undertaken. The search also included a study of more recent work, looking at present day thinking behind power line progress. Regulatory and standards issues were also investigated.

2) An investigation into the signal characteristics of a low voltage electricity distribution network. This included the characterisation of individual network elements as well as the whole network. Much of this work was carried out on one residential network in Kendal, Cumbria, where NORWEB plc, and the residents of Applerigg, provided access to their

network. Towards the end of the initial research period, a dedicated network section was installed at NORWEB's training centre in Chorley, Lancashire. Although based on a real distribution network, no customers were connected, allowing a significant increase in the type and duration of testing.

3) The development of a new and novel concept for power line communications. This included the use of frequencies above 1 MHz for transmitting information, and the proposal for the development of a conditioned network.

The main body of this thesis details the work carried out in each of the above primary work areas, in the form of case studies for the literature search, and a detailed report outlining the major milestones encountered during the course of the project.

The conditioned low voltage distribution network concept, described in Chapter four, required the development of in-line filter elements. The filter had to be capable of carrying the full UK domestic current, 100 A on a single phase, without affecting any quality of service requirements laid down by the Utilities, the Office of Electricity Regulation (OFFER) and the standards organisations. The filter construction also had to be capable of safely withstanding any potential fault currents. Whilst allowing the low frequency domestic electricity supply to pass through, the filter had to attenuate a significant proportion of the high frequency signal associated with power line communications. A mathematical model is developed in this thesis to describe the filter behaviour in the frequency range of interest and is compared with results obtained from filter tests.

In order to provide as complete a picture as possible, it is important to initially describe, in some detail, the network over which power and communication signals are to be combined. Chapter one of this thesis therefore, introduces the UK electricity distribution industry: its history, development, organisational structure and physical make up.

This chapter also looks at how the industry has changed in recent years with the advent of privatisation, deregulation and competition. The electricity supply industry, by its very nature, is monopolistic; it isn't practicable to move house if a change of supplier is wanted, and by the same token, a preferred supplier cannot install a new supply system for someone outside its home region. In order to oversee fair play and to encourage competition, the government of the day in 1989 established an independent body under the Electricity Act 1989 to regulate the electricity supply industry. The name given to this regulatory body was the Office of Electricity Regulation (OFFER). Its successor, the Office of Gas and Electricity Markets (Ofgem), was formed early in 1999 by combining the functions of the former Office of Gas Supply (Ofgas) and the Office of Electricity Regulation (OFFER).

A section on UK metering highlights the important role OFFER and its successor, OFgem, play in a deregulated environment. In 1992 OFFER produced a consultation paper covering competitive supply down to the domestic market. The paper emphasised the need to utilise new technologies in order to realise fully the benefits of a free market. In the UK, all domestic electricity customers have been able to choose who supplies their electricity since 1999. The wish to develop a cost-effective, remote meter reading system has been one of the pivotal forces driving research into power line communications, and although not the main aim of this research project, marks its starting point.

A brief history of power line communications is also included in this chapter. The overview highlights some of the significant milestones associated with the technology, and introduces a number of early projects used as case studies in Chapter two.

1.2 The Electricity Distribution Network

1.2.1 History and Development

The first British power stations were built in the 1880s and they supplied d.c. power to customers situated close to the generating plant [1.1, 1.2]. Little thought was given to differing customer requirements, and losses in the distribution network severely limited its use. The electrical resistance of the cables, although small, ensured that electricity at a safe and usable voltage level could not be transmitted very far. Two principle reasons accounted for this:

1) Electrical power was dissipated in the distribution system. The greater the distance, the greater the power required to overcome the losses.

2) It was not economically viable to produce more electricity than needed just to overcome losses in the network.

If the current could be reduced then the power loss due to cable resistivity could also be reduced.

$$\text{Power loss} = \text{Voltage dropped across the transmission line} \times \text{Current} \qquad \textbf{(Eqn. 1.1)}$$

For a given demand, if the current is reduced the voltage must be increased. With a d.c. system, the voltage levels soon become impractical, especially for those living close to a power station where losses are at a minimum. Some means were required to step the voltage up for transmission and down to a suitable level for use by the customer.

With the advent of a.c. and the development of the transformer, the above problems were largely solved. Step-up transformers allowed the electricity produced in power stations to be transmitted over large distances at a high voltage and low current. A series of step-down transformers provided a supply of electricity at a safe and useable voltage. Figure 1.1 depicts a modern distribution network from production to domestic use.

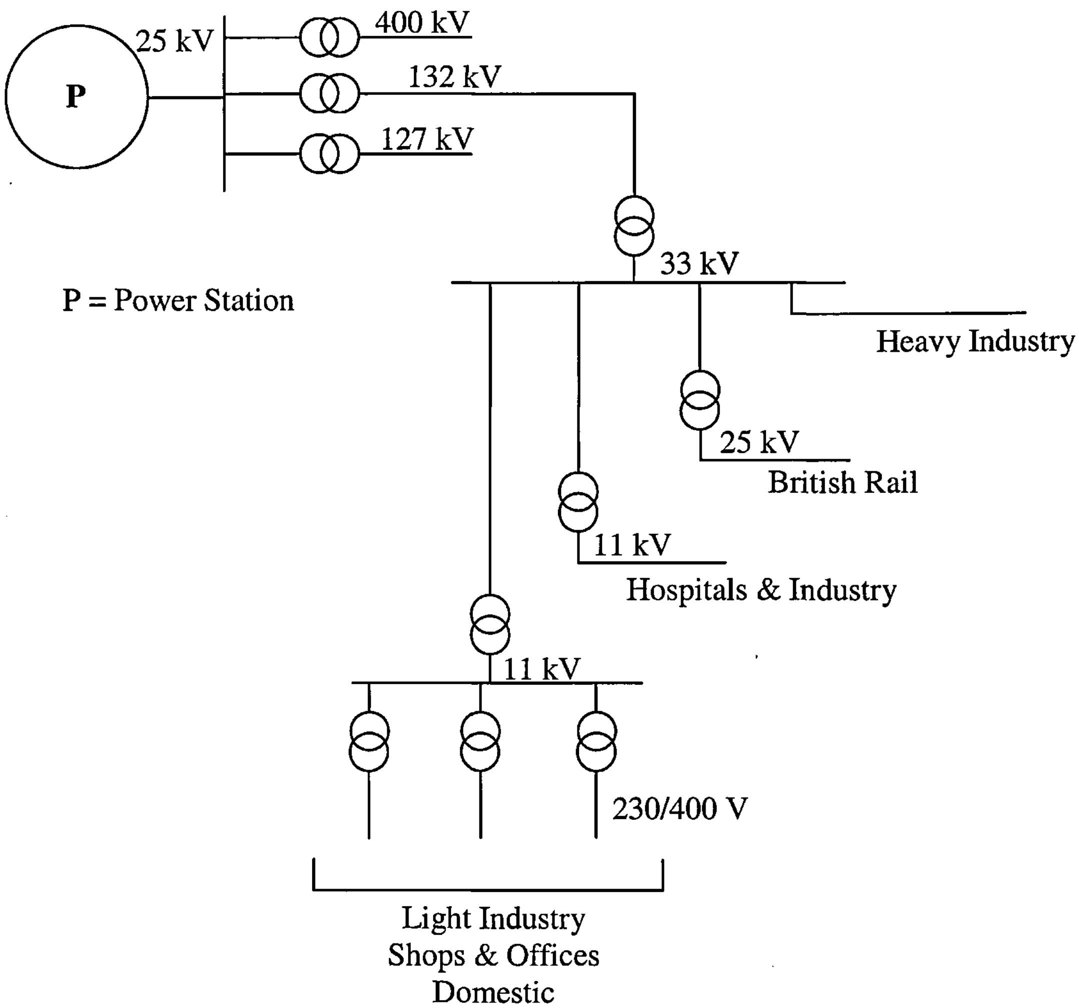


Figure 1.1: Simplified Distribution Network

In 1916 the first proposals were made to link individual power stations in Britain into a national grid. The idea behind the proposal was a simple one. By connecting all generating centres together, local shortfalls in production could be offset by surplus production in other areas. This would ensure a constant and dependable electricity supply. Such a grid also reduced the number of power stations required by making better use of available capacity.

The Central Electricity Board was established in 1926 and was instructed to build the National Grid and rationalise the supply of electricity. Construction began in 1929 and was completed in 1938.

The industry was nationalised in 1948 and from that time until privatisation in 1989 the organisational structure remained virtually unchanged. The structure contained three tiers: The Electricity Council, the Central Electricity Generating Board (CEGB) and the Area Boards.

1.2.2 The Electricity Council

The official face of the industry to the outside world. It advised the government on electricity matters and within the industry it was the forum for policy formation.

1.2.3 The Central Electricity Generating Board

This body owned and operated the power stations and transmission lines. It was responsible for bulk supplies of electricity to the various Area Boards and to selected large industrial consumers.

1.2.4 Area Boards

There were twelve Area Boards in England and Wales. They were responsible for the distribution networks and sold electricity to industrial and residential consumers.

With privatisation, competition was introduced into electricity generation and supply [1.3, 1.4, 1.5]. Operators no longer have an obligation to supply electricity, and there is no assured market. All generating companies now have to compete for their market share. In England and Wales the CEGB successor companies are no longer the only suppliers: The Scottish electricity companies, Electricité de France and a growing number of independent power operators are all generating electricity for sale in England and Wales.

In England and Wales most production comes from three generating companies created out of the CEGB; National Power and PowerGen are both fossil fuel based generating companies having approximately 30,000 MW and 18,000 MW of generating capacity respectively. Nuclear Electric, which remains in government ownership, has approximately 8,400 MW of generating capacity. The National Grid Company owns and operates the transmission system. This company is owned jointly by the distribution companies. Finally, the twelve Regional Electricity Companies (RECs) are the direct successors of the previous Area Boards. The RECs are responsible for the distribution and supply of electricity to some 22 million customers.

In Scotland there are two vertically integrated companies, Scottish Power and Scottish Hydro Electric. These were formed from the old South of Scotland Electricity Board and North of Scotland Hydroelectric Board. These two companies control generation, transmission and distribution. In addition, Scottish Nuclear operates as a generator and remains state owned.

In Northern Ireland the generating plant has been sold off to four competing generators, whilst Northern Ireland Electricity plc is responsible for transmission, distribution and supply. Figure 1.2 shows the structure of the present UK electricity generation and supply industry.

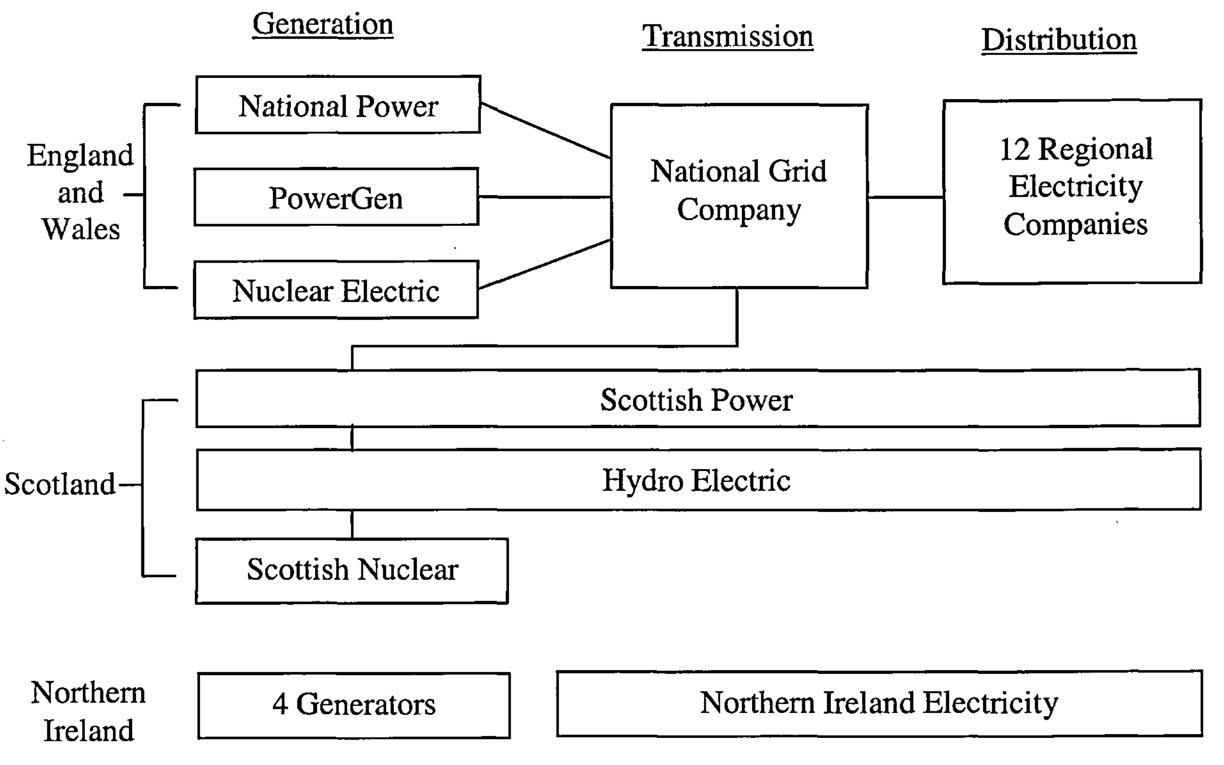


Figure 1.2: Structure of the UK Electricity Industry

1.2.5 The Pool

All major generating companies in England and Wales have to sell all the electricity they produce into an open commodity market known as 'The Pool'.

Each generating unit has to declare a day in advance its availability to produce, together with the price at which it is prepared to generate, for each half-hour of the day. The National Grid Company then ascribes generating priority to each unit in ascending order of price. The most expensive unit used sets the 'system marginal energy price', which all others receive for that half-hour. For the units who made generating capacity available to the Pool which was not used, a separate pricing mechanism exists.

1.2.6 The National Grid

The National Grid Company owns and runs the main, high voltage supergrid system. It consists of 7000 route kilometres of high voltage transmission lines and over 200 sub-stations. The primary role of the National Grid Company is to develop and maintain an efficient, co-ordinated and economic transmission system and secondly, to facilitate competition in both generation and supply.

Access to the Grid is unrestricted; however all generators and distributors seeking connection must meet the appropriate standards to ensure that technical difficulties are not caused for others connected to the system. Both suppliers and generators are charged for using the Grid. These charges cover entry, exit, system service and infrastructure costs.

1.2.7 Regional Electricity Companies

The twelve Regional Electricity Companies (RECs) in England and Wales have three main activities: the distribution and supply of electricity and electrical installation contracting. In addition, all RECs have now become involved in generating schemes mainly involved with independent generators. Distribution and supply account for about 90% of turnover.

The RECs operate two businesses associated with electricity: Distribution, which operates and maintains the distribution networks, Supply, which purchases electricity in bulk through the wholesale market and sells it to the customer.

1.2.8 Distribution

The distribution business operates and maintains the overhead and underground networks, switches and transformers operating at voltages from 132 kV down to 230 V. The distribution business is in effect a monopoly, so the charges made for the use of a RECs distribution network are subject to regulatory price control.

1.2.9 Supply

In order to supply electricity, a company requires an electricity supply licence. There are two types of licence:

1) Firstly, a Public Electricity Supply licence gives a REC rights and obligations, relating to supplies to customers within its authorised area. This is a monopoly market therefore price controls operate in a similar manner to the distribution business.

2) Secondly, a Second Tier licence gives a REC the right to supply customers outside their region. It also allows generators to supply customers direct.

Competition has also been introduced in the retail market. In 1989 the Electricity Act enabled customers with a demand of over 1 MW to negotiate individually for their electricity supplies. This allowed large users to buy their electricity from either their local REC, another REC, a generator or even the Pool itself. In 1994 the same facility was made available to the above 100 kW market. In 1999 all electricity consumers were given the ability to purchase their electricity from a supplier of their choice. For this final opening up of the electricity market to work, a new dynamic approach to metering and tariff structure is required.

1.3 Metering

In the early 1980s the UK electricity industry began investigating the possibility of altering the load curve for domestic customers, by either taking direct action using some form of load control; disconnecting specific loads at times of high demand, or alternatively, influencing customer usage by application of cost-reflective multi-rate tariffs [1.6]. Both of these solutions would require the use of electronic techniques in both communications and the implementation of required functions at the customer's premises. In particular, conventional electromechanical Ferraris disc meters were deemed unsuitable for conversion to multi-rate tariffs without excessive complexity and the consequent risk of unreliability.

There was therefore a need to develop an electronic meter with no moving parts. The development of Radio Teleswitching (ref. Chapter two) speeded up the process and led to the mass production of electronic meters in some UK meter factories in the mid 1980s. Additional benefits offered by electronic meters were also realised early on by UK Electricity Boards: an electronic meter would be far more resistant to typical methods used to steal or divert electricity. There was also a desire to replace coin operated meters because of their unreliability, theft of coins stored inside them and attacks on Utility staff collecting the cash. By the time of privatisation, 1.5 million static domestic meters had been installed.

In the mid 1980s complex tariffs were being implemented for industrial and commercial customers using 'multi-function units'. These electronic units detected pulses from conventional industrial meters and processed the information to give demand and time of use data. In 1987 Polymeters launched their CALMU polyphase meter (ref. Chapter two) which implemented the functions of a conventional meter and multi-function unit in software within a single meter. All UK manufacturers now offer polyphase static industrial meters that comply with the requirements of the 1 MW and 100 kW markets.

1.3.1 The 1 MW Market

Since April 1990 all UK electricity customers with a maximum demand above 1 MW, some 4,500 customers, have been able to purchase their electricity from a supplier of their choice. Metering equipment was installed to record half-hourly consumption readings, this information is passed on to data processing centres where consumption can be related to prices in the Pool. The data is collected from each customer by nightly polling, access being via the public telephone network or, in some cases, a cellular data network.

Where a customer chooses to obtain his electricity from a second tier supplier (a supplier from outside his local area) a number of arrangements have to be made in order to ensure all concerned parties obtain correct payment for facilities used.

(1) There is a supply contract between the customer and the supplier. The latter requires metered data on which to base charges for electricity consumed.

(2) There is a connection agreement between the customer and the local REC.

(3) There is a use of system agreement between the local REC and the supplier. The local REC requires metered data so that it can bill the supplier for using its distribution system.

(4) The supplier purchases electricity from the Pool. This requires metered data relating consumption to the half-hourly pricing system in the Pool.

Each second tier supplier bills its own customers and pays for the following items from the money received:

(1) The second tier supplier pays at Pool prices for the units of electricity taken.

(2) It pays the local REC use of system charges.

(3) It pays the meter operator's charges. These charges are based on the capital cost of metering equipment, the provision of data acquisition and communication equipment and expenses of site installation, testing, commissioning and maintenance.

(4) The supplier pays the National Grid Company a Second Tier System Charge.

1.3.2 The 100 kW Market

In April 1994 all electricity customers with a demand in excess of 100 kW were also given the opportunity to buy their electricity from a supplier of their choice. This added a further 50,000 customers to the open electricity market. Possible second tier customers above 100 kW include companies with multiple sites such as chain stores, some local authority properties and some hotel chains. In addition, it may include many medium-sized customers whose total savings from a competitive supplier will be less than those of larger customers. These companies will be far more sensitive to the cost of metering and communication systems.

The arrangements for metering and data collection for the 1 MW customers came under criticism by some parties as being too costly and presenting a barrier to competition. As already stated the above 100 kW market is far more sensitive to the cost of metering and data collection, therefore a more economically viable metering system was required. In the event, the recording of consumption data every half-hour was retained, but the specification for metering equipment at the customer's premises was reduced. The payment and agreement structure remains similar to that described for the 1 MW market.

1.3.3 Full Competition

In 1999 all 22 million UK electricity customers became eligible to take competitive supply. If cost is a constraint in the 100 kW market, then it is an even tighter constraint in the domestic market.

At present four main parties require data for competitive purposes: the Pool, the local REC, the supplier and the customer. There is no reason to believe that this requirement will change for the domestic market. Even if the present system is pared down to a minimum there is a fear that a potential 22 million customers will exceed the system capability with the amount of data requiring processing.

In 1992 the Office of Electricity Regulation (OFFER) issued a consultation paper [1.7] which proposed that the arrangements for competitive supply down to the domestic level called for the installation of a two-way communication infrastructure to support new technology metering at the customers premises. The paper envisaged remote meter reading and load control controlled through a two-way communications network based on existing telephone wires, future cable TV facilities, radio communications and mains signalling. It suggested benefits both to the customer and to the supplier, which could offset the cost of such equipment, though no specific values were assigned to these benefits.

Remote meter reading and new technology would allow an increase in the frequency of meter reading. This, the paper suggests, could lead to more frequent and accurate billing. There would be no estimated bills, and reliable real-time information about the status of accounts could be accessed. There should be a marked improvement in fault diagnosis, with the supplier alerted as soon as a fault occurred. The supplier could also be informed if anyone tried to tamper with a meter.

Work is currently under way within the IEC and CEN/CENELEC to produce international standards, which define communications architectures and protocols to meet Utility requirements for metering communications.

1.4 The History of Power Line Communications

The idea behind using power lines as a medium for delivering more than just electric power dates back to the early 1920s. In those early days, high voltage cables were considered to be a possible alternative to installing expensive pilot wires, especially in remote areas where distances of a few hundred kilometres were not uncommon. The need for remote network monitoring and control may have been the driving force, but even then, voice circuits were under consideration.

With only a few exceptions, signalling on power lines was restricted to networks of greater than 11 kV, where lines tended to run point to point between substations. At 11 kV and below, spur lines and transformers caused high signal attenuation [1.8, 1.9].

Traditionally, frequencies below 150 kHz have been used. This was eventually formalised in the Electro-Technical Standardisation body, CENELEC, EN 50065-1 [1.10]. Radiated signal strength has always been considered a problem and therefore frequencies were chosen so as not to interfere with services such as aircraft navigational aids, broadcast radio and open-wire telephone systems. Services only requiring a very short time slot at long intervals, such as carrier-feeder protection, were allowed to use power levels and frequencies that could not be tolerated for speech and telemetering systems.

By the 1950s low frequency power line technology was widely used on high voltage networks for the transmission of Supervisory Control, Remote-Indication, signalling associated with protective and intertripping equipment, and the transmission of speech. Power line coupling equipment was large and expensive; the decision to install a power line solution instead of pilot wires was based on cost. As a result, power line techniques were mainly utilised in remote areas where alternatives were not available, making PLC cost effective.

The cost of high voltage coupling equipment came from the fact that it was installed either in series or parallel with the high voltage circuits. In-series line choke coils had to carry the power line load and have the ability to withstand currents under fault conditions; coupling capacitors had to withstand line voltages.

Both phase-to-phase and phase-to-earth transmission techniques were available, and once again the cost of each was an important factor. However, for those companies who could afford it, phase-to-phase transmission was the preferred solution for the following reasons:

- Signal attenuation was reduced and consistent.
- A much better signal-to-noise ratio was achieved.
- Variations in signal attenuation due to weather conditions is greater when using phase-to-earth techniques.
- On a phase-to-earth system, a fault on the phase conductor could result in the loss of signal. With phase-to-phase coupling the loss of one of the phase conductors results in only a slight increase in signal attenuation.
- Radiated signal from a phase-to-phase system is much smaller than that for a phase-to-earth system.

The cost of phase-to-phase transmission was greater due to the fact that twice as much high voltage coupling equipment was required.

The networks talked about so far have been high voltage overhead networks with few, if any, discontinuities. These networks provided the most stable environments for power line communications. However, noise interference had also to be taken into consideration. The main interference source came from corona and arcing which resulted in wide-band noise reducing the signal to noise ratio. The situation was made worse by bad weather. However even in adverse conditions, acceptable signal-to-noise ratios were available over sections of high voltage network in the order of 185 km in length. Another source of noise came from switching and isolation operations, which produced wide-band noise and surges of considerable amplitude. Their short duration however meant their adverse affects were short lived.

One of the exceptions to the greater than 11 kV rule, and one power line technology that has enjoyed modest success, was the development of Ripple Control, which superimposed audio frequency (AF) tones onto the low voltage power signal in order to transmit simple 'on' 'off' instructions. Ripple Control was first investigated by the power board of Davos, Switzerland, in 1929. The mains frequency was modulated with a burst of AF signal, each burst lasting for the duration of several mains frequency cycles. A number of these AF bursts were joined together to form a signal code which could be received and deciphered at various points throughout the network. The system was used to switch on and off, large numbers of similar units such as streetlights, water heaters, shop illuminations and multi-tariff meters.

Different audio frequencies were used for different applications allowing a number of services on the same system. Tuned circuits in the receiver equipment detected only signals relevant to its operation. Ripple Control equipment was still being manufactured by Landis and Gyr in the late 1960s.

Modulating the mains signal with AF signals required equipment that was large, costly and required regular maintenance. In the late 1950s a system offering economic attractions and minimal size and maintenance requirements was devised. Peak Depression arranged discreet marking of selected cycles of the 50/60 Hz mains, rather than modulating the mains with a unique signal frequency. Marking was achieved by applying a limited and precisely controlled short circuit. The short circuit drew heavy current for a few microseconds at a precise pre-selected position on the voltage wave. The pulse current, 200 to 300 A, had a sharp leading edge and saw the system as a high impedance with excellent propagation characteristics. A series of pulses was arranged to form the telegram. A complete telegram comprised 3 impulses discretely placed within a 16-cycle period of the 50/60 Hz supply. As Peak Depression signalling developed it was determined that restricting the modulation to a small area around voltage zero prevented disturbance/interference to sensitive loads connected to the mains, for example lighting and television. It also reduced signal attenuation to a minimum, allowing signals to be correctly received throughout the network. This technique, known as Cyclocontrol, increased the complexity of the coding in order to allow addressing. In 34 mains supply cycles, 165 discreet addresses were available with four possible instructions.

Ripple Control and its successors have been used on networks around Europe for many years, and although somewhat dated, operational examples can still be found today.

In 1936 Bell Telephone Laboratories began investigating the possibility of using power lines as a means of providing a telephone service to rural customers in sparsely settled areas of the United States. Initial investigations using voice frequencies proved impracticable due to the high transmitting power required to overcome ambient noise levels. Efforts were therefore focused on high frequency techniques where power line noise levels were less of a problem. The frequencies used were between 150 kHz and 455 kHz. At frequencies below 150 kHz coupling problems became increasingly difficult, and at frequencies above 455 kHz high line attenuation and interference from broadcasting stations limited the usefulness of the system.

The system was designed to work on the typical US rural distribution network, made up of a single-phase pole-mounted conductor, operating at 7 kV and 60 Hz, with a lower neutral wire that was grounded at frequent intervals. The system could work on networks that were up to 20 miles (32 km) in length. Due to the large number of taps and branches associated with a distribution network, a series of in-line isolating and transmission chokes were required in order to reduce signal attenuation to a minimum.

The project was abandoned in 1941 with the entry of the USA into the Second World War but reinstated in 1945. By October 1946 the Bell team had developed a power line telephone system known as the M1 Carrier Telephone System which was manufactured by the Western Electric Company.

Over the last thirty years, development work has concentrated primarily on automatic distribution functions such as automatic meter reading, selective load control and demand-side management. All of this work has fallen within the CENELEC band of frequencies and has been led by university and utility based research projects. The overall desire has been to develop a system capable of helping the utility change the shape of its demand curve. By levelling out the twenty-four hour demand curve, electricity producers can reduce the cost of production. Peaky demand such as at meal times requires the use of plant that is quick to come on line but expensive to run. Examples of this type of plant would be gas fired power stations. If the demand for electricity could be made more even and spread throughout the entire twenty-four hour period, cheaper generating plant could be better utilised, the overall cost of implementing such a system being justified by the savings in production costs. On the back of this network management system, other services could be operated that financially could not be justified on their own such as automatic meter reading and network monitoring. Almost without exception these projects have led to a better understanding of power line characteristics and issues but have not resulted in widely available products and services. The following examples are representative of the type of project work undertaken by utilities up until the early 1990s.

The Wisconsin Electric Power Company in the US, investigated the possibility of using power line carrier over its distribution lines in order to implement a load management system in the mid 1970s. The system was designed for the remote reading of electricity, water and gas meters equipped with suitable digitising encoders. Loads such as water heaters and central air conditioners could also be controlled via auxiliary switching units. A domestic transponder could service up to four switchable loads and three different meters. For one of the meters, registers were available for implementing 'time of day' metering with a rate structure of two or three periods and memory of peak demand for a selected period.

Credit and Load Management Systems (CALMS) was developed by the South Eastern Electricity Board in the UK in the early 1980s. Based around an 'intelligent' home terminal and using a number of different communication media, CALMS was not dependent upon power line communications alone. The system was designed to give more accurate information to both the customer and the utility, enabling the utility to make better use of its resources and the customer to monitor the cost of electricity and tailor usage to benefit from multi-rate tariffs offering cheaper electricity at various times of day. The services offered were as follows:

- Measurement and recording of demand and maximum demand.
- Remotely selectable tariffs.
- Calculation of outstanding charges for continuous display to the customer.
- Provide electrical loading and demand information to assist in the network planning and control.
- Ability to institute tariff and price revisions remotely.
- Remote reading of a 3-rate meter.
- Accept customer payments remotely.
- Apply load limits for use in tariffs or in system emergencies as an alternative to rota disconnection.
- Remote reading of gas and water meters.
- Earth leakage protection facilities at customer's premises.

In the UK in the mid 1980s a consortium made up of representatives of the electricity, gas and water industries, THORN EMI and supported throughout by the Department of Trade and Industry, The Department of Energy and Ewbank Preece Consulting Ltd, ran field trials on a mainsborne telecontrol system. THORN EMI were commissioned to design and manufacture microprocessor based equipment for the 1000 user trials, they opted for using a form of spread spectrum signalling to overcome the problems of noise on the low voltage distribution network. Until this time, spread spectrum signalling had been used almost exclusively for military communications.

The trial system offered the following functions:

- Multi-tariff registers for each of the electricity, gas and water meters.
- Two contactors of 25 A and 80 A switching capability for control of water and space heating loads.
- 24 hour, half-hourly consumption registers for analysis of load pattern variation.
- Display of time, consumption of electricity, gas and water, cost and quarterly bill prediction.
- Provision of override facilities for the customer to control water and space heating loads.
- Tamper detection.

The conclusions of the trials working group were positive, and listed a number of reasons for continuing the development of a mainsborne telecontrol system.

In the late 1980s, Italy's largest electricity utility, ENEL, set down the specifications for a trial on their network. The purpose of the trial was to demonstrate the feasibility of using the low voltage network as a data transmission medium. Three companies from the IRI-STET group were employed to develop and investigate the technology, they were Esacontrol, Italtel-SIT and SGS Microelettronica. The driving force behind the project was the desire to optimise the use of resources available for generating electrical power and to control user consumption. The system was designed to provide the following services:

- Frequent remote reading of consumption data for connected users.
- Daily updating of different charge bands.
- Power consumed by individual users limited to a contractual value.
- Peak power delivered during a one-month period recorded.
- Power consumed by all connected users limited to help resolve critical conditions of availability.
- Power delivered by substation and the sum of the powers delivered to individual users compared to evaluate network losses.
- Notification of any attempt to tamper with supply.

Datawatt's Robcom system was developed in the Netherlands in the late 1980s and early 1990s. The system was tested in the Netherlands and Switzerland. Robcom used frequency hopping spread spectrum and covered both the medium voltage and low voltage networks. The system was designed to support Distribution Automation on the medium voltage network and Load Management on the low voltage network. On the medium voltage network the following services were offered:

- Monitoring of energy flows at various points along the network.
- Fault location.
- Continuous measurement and control of voltage levels throughout the network.

On the low voltage network the following services were offered:

- Tariff switching.
- Load shedding.
- Load cycling.
- Remote meter reading.
- Fault location.

Chapter two uses case studies to look in more detail at the development of power line communications. As mentioned earlier, the desire to modify the twenty-four hour demand curve has been a significant influence in the development of the technology and therefore most of the following case studies are related to automatic meter reading, selective load control and demand-side management. Power line communications were not seen as the only solution to the above requirements, and so one or two examples of alternative technology solutions are included for completeness.

Chapter 2: PLC Case Studies

2.1 Introduction

Chapter two looks in more detail at the history and development of Power Line Communication. A number of selected case studies are used which document key stages in the development of Power Line Communication. Some studies outline the development of particular coding and transmission techniques, whilst others review specific product solutions.

In more recent times, advances in technology have introduced alternatives to remote meter reading and load control via the distribution network. These include:

- Remote control of load and tariff switching using broadcast radio signals.
- The use of telephone lines to transfer metering and load control information whilst not required for telephony, a technique known as Idle-Line Working.
- Meter reading using simplex radio transmission.

2.2 Early Signalling Techniques

2.2.1 Ripple Control

Ripple Control was first investigated by the electrical power board of Davos, Switzerland, in 1929 [2.1]. In order to utilise the low voltage network for communication purposes, the mains frequency was modulated with a burst of AF signal, each burst lasting for the duration of several mains frequency cycles. A number of these AF bursts were joined together to form a signal code which could be received and deciphered at various points throughout the network.

2.2.1.1 Audio Frequency Generators

Asynchronous motor-driven audio-frequency generators, known as rotating frequency converters, were used up until the mid 1960s. From 1967, static frequency converters were used. The static frequency converters were synchronised using the 50 Hz mains frequency as a reference. Being non-mechanical they promised a longer and more reliable life.

2.2.1.2 Signal Coding

In 1929 the initial investigations into power line signalling were directed towards the use of Frequency Multiplex Coding. However by 1931 the emphasis had changed with the introduction of a technique known as Impulse Count Coding.

In 1934 in Zug, Switzerland, impulses were injected into the low voltage network between neutral and ground. At the sending end a command was chosen by pushing a particular button, this was converted into a number of impulses, which were injected onto the low voltage network. Each command was allocated a unique number of impulses. At the receiver a relay detected the impulses which drove a rotary counter which in turn decoded the command message.

In 1936 a new coding technique was introduced called Impulse Interval Coding. This new technique enabled a relatively large number of commands to be transmitted over one channel; it also reduced the complexity of the electromechanical receivers and increased their expected lifetime.

2.2.1.3 Impulse Interval Coding

Command recognition is achieved by checking the time difference between the start impulse and one or more impulses during a 25 second transmission period. A total of 50 distinct time stages are available.

Impulse Interval Coding offers two possible coding techniques:

1) Direct Selection.

Direct Selection coding utilises the start pulse and a single command impulse. This allows for 50 single messages or commands. If each command is divided into its on and off states (these are known as Double Orders), 25 possibilities exist.

2) Group Selection.

Group Selection coding is far more flexible than Direct Selection. In this system a start pulse and two or more impulses are required for command recognition. This allows each receiving station to have a unique address. Addresses are indicated by one or more impulses in the first five seconds after the start pulse, see figure 2.1. A single impulse in the remaining 20 seconds indicates the command to be implemented. Each command is split into an on/off double command.

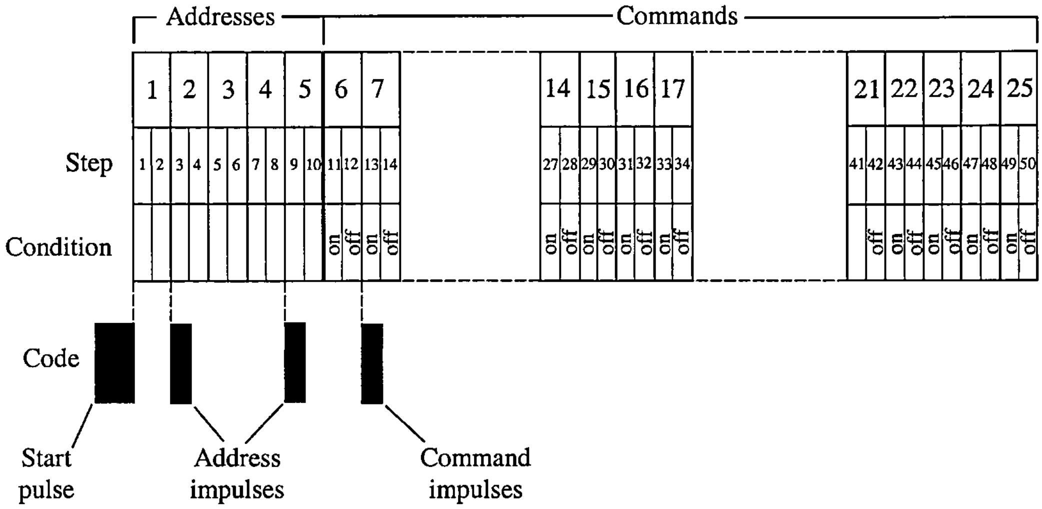


Figure 2.1: Impulse Interval Coding

2.2.1.4 1970s Ripple Control Transmission Equipment

The transmission equipment can be broken up into four basic units:

- Central Programming Unit.
- Transmitter Remote Control Unit.
- Frequency Converter Unit.
- Coupling Filter.

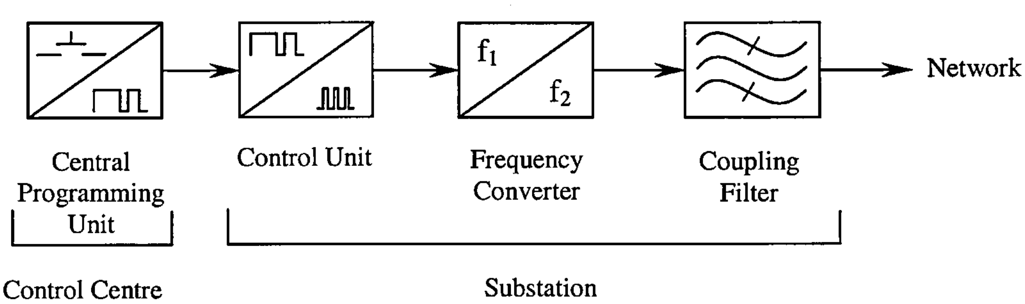


Figure 2.2: Transmission Equipment

2.2.1.5 Central Programming Unit

Before each transmission, the Central Programming Unit conveys the start signal to the injection equipment and then initiates the programmed impulse telegram. The Central Programming Unit also provides central supervision of the injection equipment and the transmitted impulses.

2.2.1.6 Transmitter Remote Control Unit

If ripple control transmitters in remote locations have to be controlled by a Central Programming Unit, remote control equipment is required both at the control centre and in the substation. The control unit supplies the triggering impulses for the thyristors in the frequency converters.

2.2.1.7 Frequency Converter

The static frequency converter is supplied by the three-phase low voltage system and generates the necessary AF power.

2.2.1.8 Coupling Filters

The role of the coupling filter is (1) to isolate the injection equipment from the mains voltage, and (2) to act as a bandpass filter allowing AF signals to pass whilst blocking the power frequency.

2.2.1.9 Receivers

Ripple control receivers consist of three basic elements:

- Input Circuit.
- Decoder.
- Load Switch.

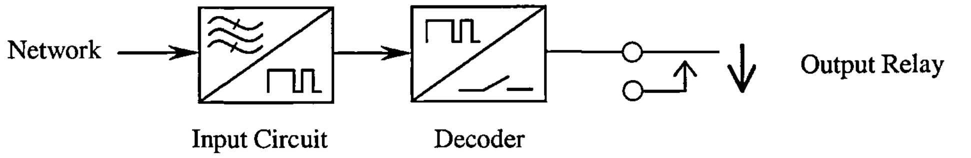


Figure 2.3: Ripple Control Receiver

2.2.1.10 Input Circuit

The input circuit is a bandpass filter, blocking power supply harmonics whilst allowing audio frequencies to pass through to the decoding unit.

2.2.1.11 Decoder

The length of each start pulse is measured to ensure that false triggering does not occur. If the address impulses match, the command impulse is implemented via a bistable load switch.

2.2.2 Peak Depression

Peak Depression [2.2] was developed in the late 1950s and offered many advantages over its forerunner, Ripple Control. Discrete marking of selected cycles of the 50 Hz power signal was employed rather than modulating it with a unique signal frequency. Marking was achieved by applying a limited and precisely controlled short circuit. The short circuit drew heavy current for a few microseconds at a precise pre-selected position on the voltage wave. The pulse current, 200 to 300 A, had a sharp leading edge and saw the system as a high impedance with excellent propagation characteristics. The pulses were generated and injected on to the system by triggering a thyristor. The circuit and resulting wave deformation can be seen in figure 2.4.

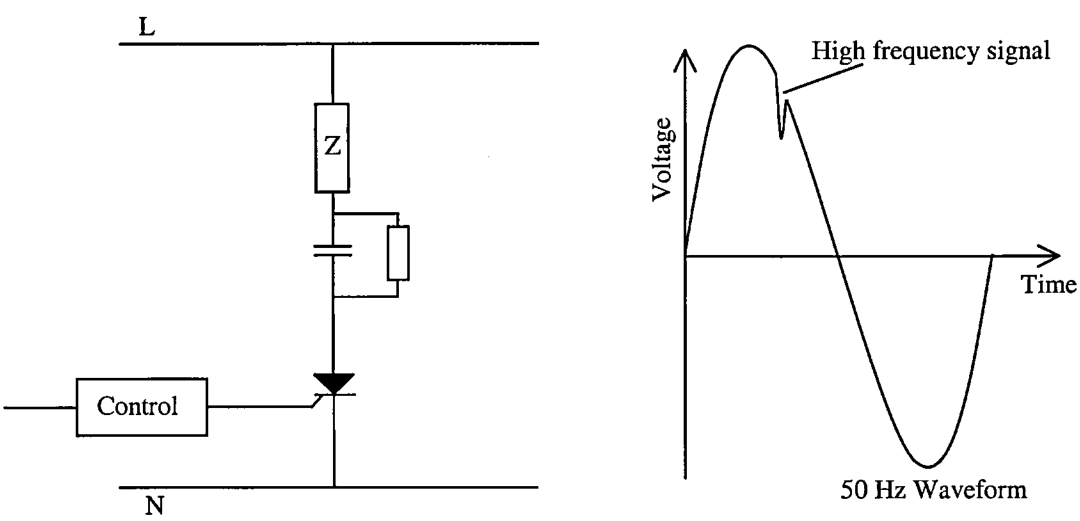


Figure 2.4: Waveshaping Circuit and Resultant Waveform

Early tests concluded that signals travelled long distances along unloaded or lightly loaded cables, while in densely loaded systems signals travelled shorter distances. Attenuation resulted from cable loading and interconnection with other supplies.

2.2.2.1 Transmitter

Transmitter design is shown in figure 2.5. The thyristor load circuit of capacitor and resistor (see figure 2.4) pass a current of about 250 A for approximately 30 μs. This causes a sharp voltage drop across the reactance of the supply transformer. The thyristors are triggered on selected positive half-cycles on each phase at 108° after voltage zero. With reference to figure 2.5, scaler (A) counts at mains frequency and allows any individual or combination of individual half-cycles to be selected. Scaler (B) registers the chosen half-cycle and arranges for the thyristors to operate sequentially through the three phases.

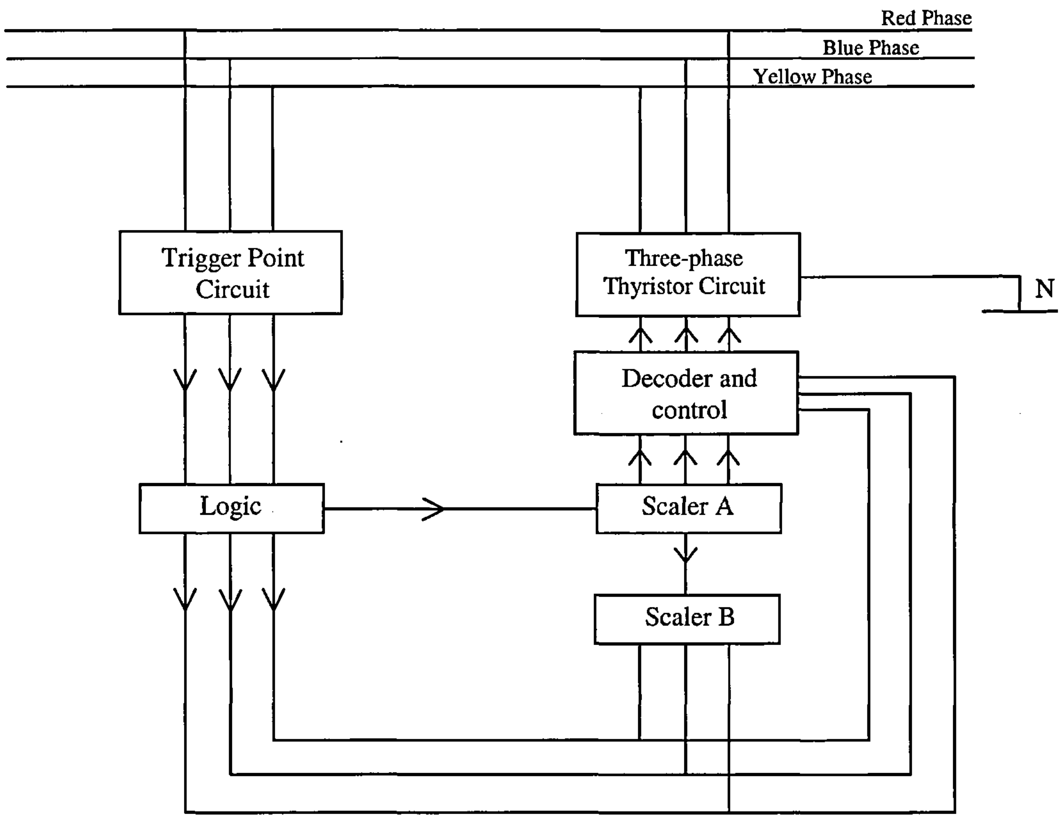


Figure 2.5: Peak Depression Transmitter

2.2.2.2 Receiver

Receiver design is shown in figure 2.6. The scaler is driven by the 50 Hz waveform. Selected outputs feed the coincidence logic circuit which compares incoming high frequency pulses with a pre-arranged code pattern. The first acceptable high frequency signal enables the scaler to progress at the 50 Hz rate. Valid pulses, received in correct positions, inhibit the resetting of the scaler and permit it to progress to the end of the count.

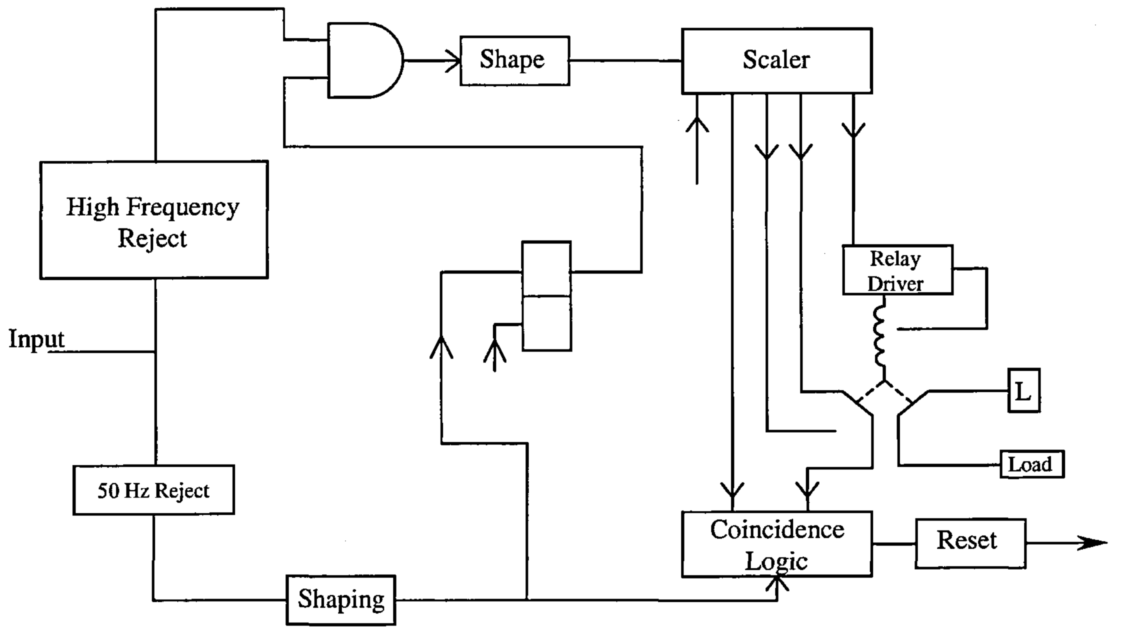


Figure 2.6: Peak Depression Receiver

2.2.2.3 Coding

A series of pulses are arranged to form a telegram. A complete telegram comprises 3 impulses discretely placed within a 16-cycle period of the 50 Hz supply. This allows for 120 different code allocations; the last four output positions of the 16-cycle code are decoded to provide an output pulse to drive the relay circuit.

2.2.3 Cyclocontrol

As Peak Depression signalling developed it was determined that restricting the modulation to a small area around voltage zero prevented disturbance/interference to sensitive loads connected to the mains, for example lighting and televisions. It also reduced signal attenuation to a minimum, allowing signals to be correctly received throughout the network.

As with Peak Depression, Cyclocontrol [2.3, 2.4] modifies the mains waveform by applying a short circuit for a short period. But in this case the thyristor is switched at an angle θ just before a negative to positive going zero crossing. In practice $\theta = 335^{o}$. At this angle, the prospective short circuit current through the choke R_c, L_c, shown in figure 2.7, is nearing a maximum. However the d.c. component of the resultant switching transient limits this current to a relatively small value, as can be seen in figure 2.8(a). The thyristor switches off at the first current zero. The switch current flows for a period which is almost symmetrical about the supply voltage zero point. The supply voltage depression across the thyristor which results from the short circuit is attenuated by the potential divider effect of the transformer and choke. The resultant distribution waveform can be seen in figure 2.8(b).

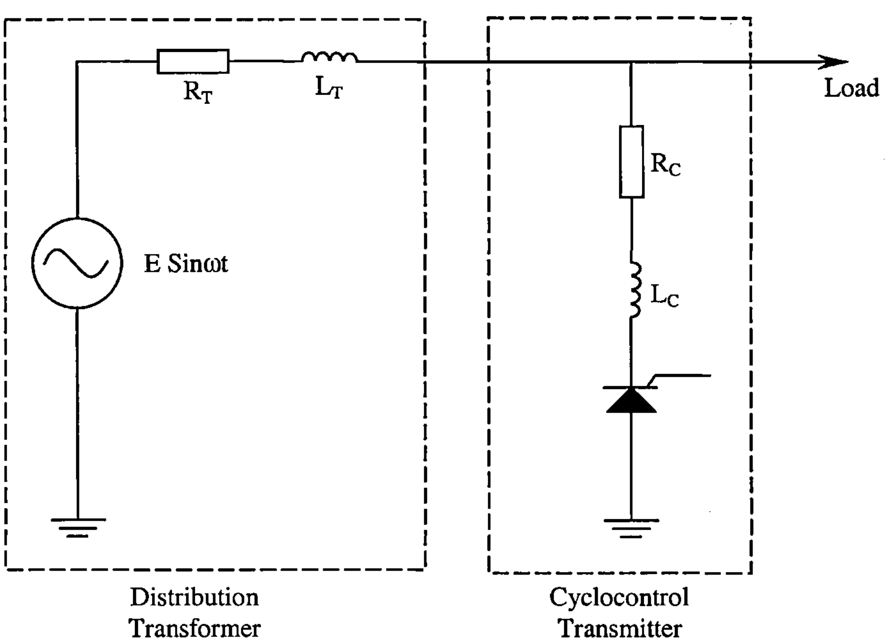


Figure 2.7: Signal Injection: Simplified Equivalent Circuit

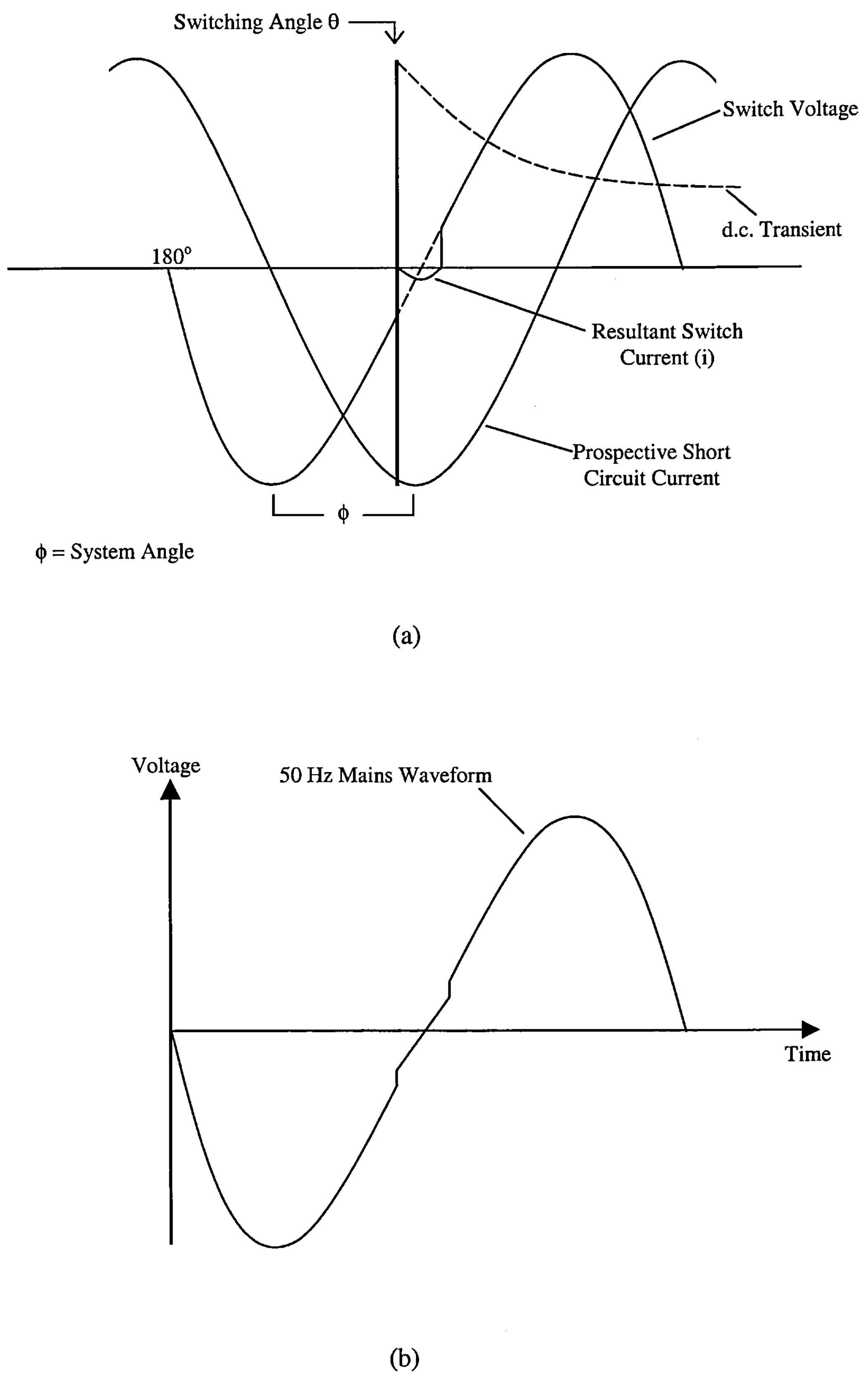


Figure 2.8: (a) Signal at the Transmitter (b) Modified Distribution Waveform

At the receiver, the waveform distortion is attenuated to the extent that it appears as a slight distortion about the zero crossing. The method used to detect the signal is to integrate the voltage waveform from about 1 ms before the positive-going zero until the positive-going zero. Alternatively the integral can be taken over 1ms from the positive going zero. This is done every mains cycle and successive integrals are compared. Therefore individual code bits are transmitted on alternate cycles. If the present integral, I_n, is smaller than its predecessor, I_{n-1}, by a pre-set amount, S_T, the receiver registers a "1", i.e. if:

$$I_{n-1} - I_n > S_T \qquad \textbf{(Eqn. 2.1)}$$

For the purpose of system comparison a percentage signal strength is defined as:

$$S = \frac{I_{n-1} - I_n}{I_{n-1}} \times 100\% \qquad \textbf{(Eqn. 2.2)}$$

Typically, S is of the order of 10% at points away from the transmitter and the signal can be reliably detected if it is greater than about 3%.

2.2.3.1 Coding

The code spans a period of 34 mains supply cycles which corresponds to a period of 0.68 seconds. After the start bit, three code bits indicates one out of a possible 165 addresses, the address is followed by one code bit which indicates one out of a possible four instructions. The stop bit is the only bit to be transmitted on a positive cycle, this increases code security by ensuring a code bit is not mistakenly decoded as a stop bit. To reduce even further the probability of a message being received in error, messages are normally transmitted twice.

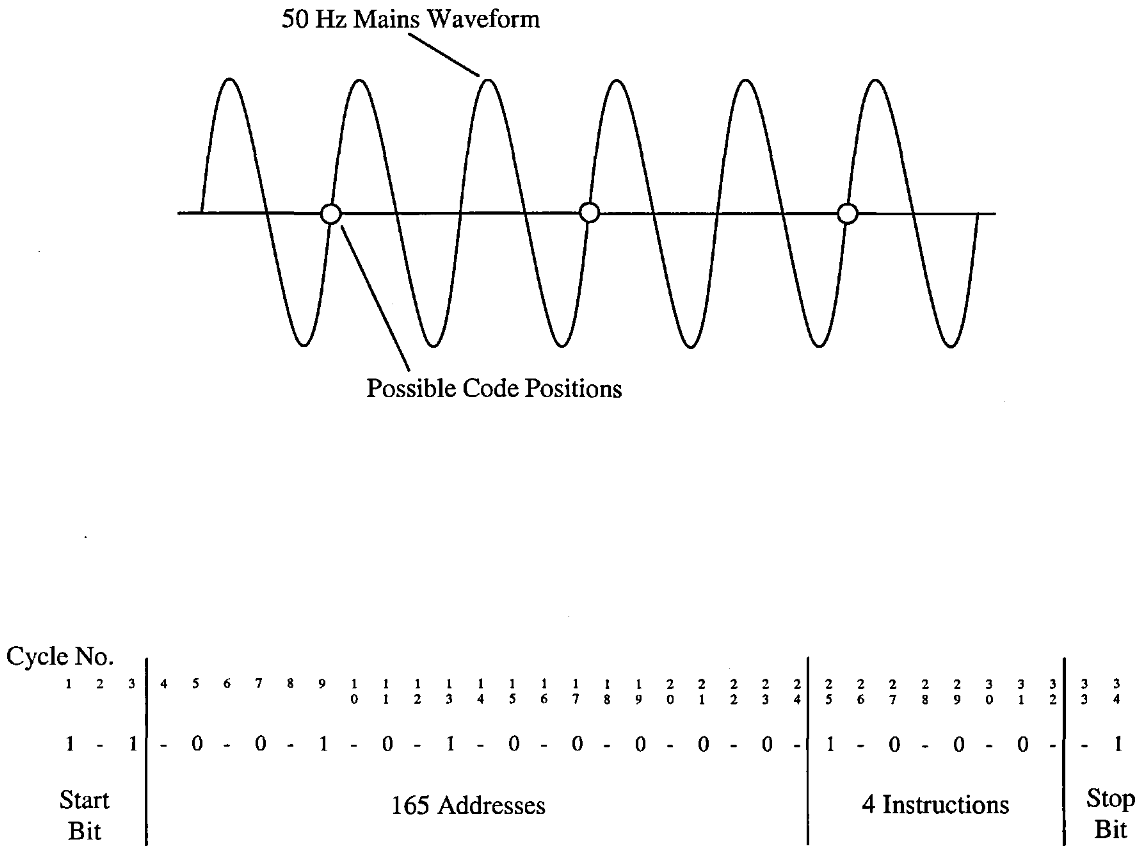


Figure 2.9: Cyclocontrol Transmission Code

2.3 An Early Power Line Telephone System

In 1936 Bell Telephone Laboratories began investigating the possibility of using power lines as a means of providing a telephone service to rural customers in sparsely settled areas of the USA [2.5]. Initial investigations using voice frequencies proved impracticable due to the high transmitting power required to overcome ambient noise levels. Efforts were therefore focused on high frequency techniques where power line noise levels were less of a problem. A technique for transmitting carrier currents over high voltage power lines had been developed prior to 1936. However the circuits required were relatively expensive, thereby defeating the object of the exercise, that of providing a relatively cheap telephone service.

The project was abandoned in 1941 with the entry of the USA into the Second World War. After the war there was a large demand for telephone services and in 1945 the project was reinstated. The project team was instructed to find the best compromise between cost, performance and ruggedness, with an emphasis on reliability. By October 1946 the team had developed a power line telephone system known as M1.

2.3.1 The Distribution System

The rural distribution system with which the project team was mainly concerned, was two-wire pole-mounted, the upper wire being a phase wire rated at 7 kV at 60 Hz and the lower wire being the neutral wire, which was grounded at regular intervals. Figure 2.10 illustrates a possible single-phase rural distribution system.

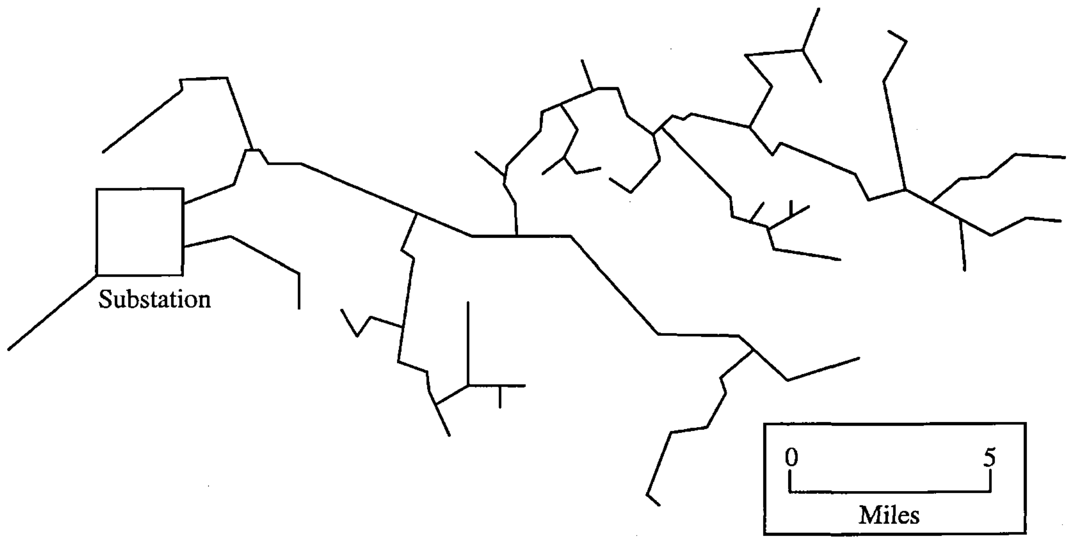
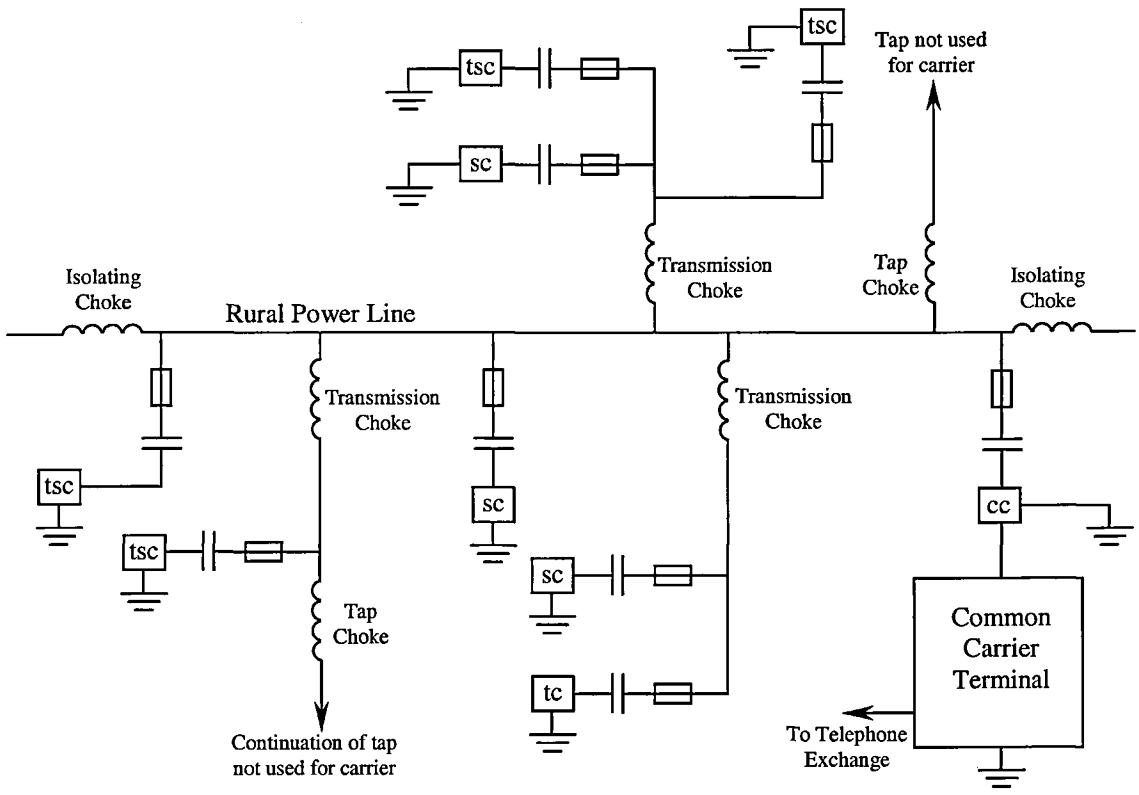


Figure 2.10: Rural Distribution Network

The distribution system was 'electrically long' at carrier frequencies; that is, the physical length of the lines could be many times the carrier wavelength. Therefore every branch of the network was a potential source of high attenuation to any high frequency signal. In order to improve the transmission characteristics of the network carrier frequency, choke coils and carrier frequency terminations were placed at strategic points throughout the network.



cc - Common Coupling Unit.

sc - Subscriber Coupling Unit.

tsc - Terminating Subscriber Coupling Unit for all end stations.

tc - Terminating Coupling Unit for ends of taps where no station is located.

Figure 2.11: Conditioned Network

Along any section of distribution network a ‘main line’ was selected, along which a carrier telephone service would be offered. A service was also offered to branches and taps off the main line. The main line was terminated at carrier frequencies in the line’s characteristic impedance (500 Ohms) at each end. Isolating choke coils were also inserted at each end. At branches and taps not used for carrier transmissions, a choke coil was inserted. Branches and taps used for carrier transmissions were terminated in the line’s characteristic impedance at, or beyond, the location of the last subscriber. In addition, transmission chokes were inserted at each tap point.

With the above modifications, a carrier telephone system could be implemented on a rural distribution system having a maximum overall length of approximately 20 miles, depending on the number of taps, ground resistivity, type and size of line wire. Figure 2.12 shows attenuation results obtained from a 14 mile long distribution line both before and after modification.

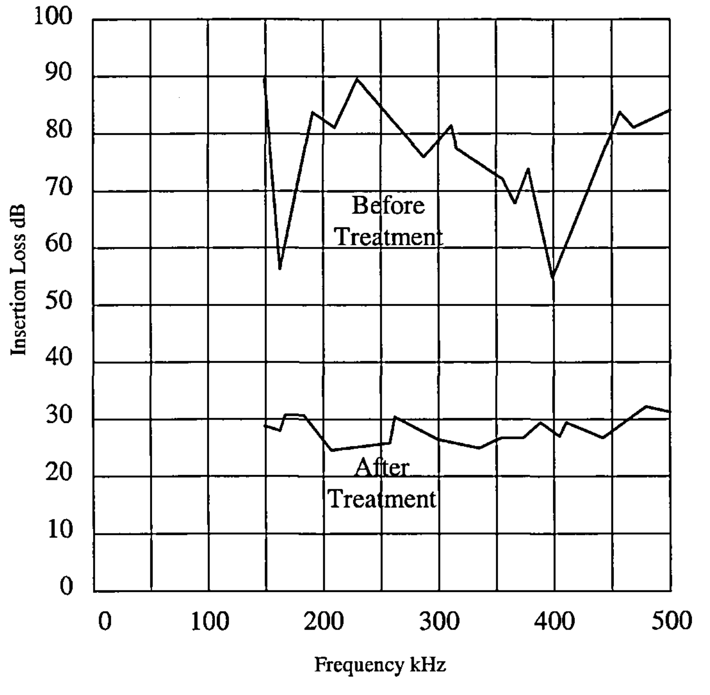


Figure 2.12: Attenuation Characteristics Before and After Conditioning

2.3.2 The Telephone System

The transmission technique used for the M1 telephone system was double side-band with transmitted carrier. This technique was chosen for its simplicity, low cost and ease with which it could be integrated with Bell's existing local telephone system.

The frequency range 150 kHz to 455 kHz was chosen. Below 150 kHz coupling problems increased whilst above 455 kHz signal attenuation and interference from broadcasting stations limited the systems usefulness. Within this frequency range six full duplex channels were provided, each making use of three carrier frequencies. A subscriber would be allocated one of a possible six receiving frequencies in the range 150 kHz to 230 kHz and one of a possible six double transmitting frequencies in the range 290 kHz to 450 kHz. Each pair of transmitting frequencies was separated by 10 kHz. One of the transmitting frequencies was used for telephone calls to parties on the normal telephone network and also for parties on the same power line system but on different channels. The second transmitting frequency was reserved for reverting calls; that is, calls made to another party sharing the same channel.

Up to eight subscribers would be allocated to each channel giving a possible 48 subscribers on a complete carrier system. Each carrier channel was connected to the telephone exchange via a voice frequency line. Each channel consisted of a common carrier terminal and a common coupling unit with coupling capacitor and fuse. Each subscriber had a subscriber terminal and a subscriber coupling unit with coupling capacitor and fuse.

2.3.3 Common Carrier Terminal

The common carrier terminal contained an oscillator modulator, transmitting amplifier, two receiving amplifiers, demodulators, ringing circuit, filters, relays, hybrid coils for combining the incoming and outgoing signals on the same voice frequency line and power supply.

2.3.4 Common Coupling Unit

The common coupling unit consisted of a carrier transformer and associated safety switch and protector.

2.3.5 Subscriber Terminal

The subscriber terminal contained a carrier-frequency oscillator, modulator, transmitting amplifier, receiver amplifier, demodulator, filters, relays and power supply.

2.3.6 Subscriber Coupling Unit

The subscriber coupling unit consisted of selective filters, relays, carrier frequency transformer and associated safety switch and protectors.

Both the subscriber terminal and the common carrier terminal required mains power. Under standby conditions the subscriber terminal used 7 watts and the common carrier terminal used 16 watts. During use, the subscriber terminal used 25 watts whilst the common carrier terminal used 30 watts.

2.3.7 Method of Operation

(1) Assuming that the carrier channel was not busy, for a call from a carrier subscriber to a voice frequency party or a carrier party not on the same channel, the method of operation was as follows.

Lifting the telephone handset off the cradle energised the carrier transmitter. The normal subscriber's transmitting frequency (F1) was selected and transmitted over the power line and detected by the common carrier terminal. At the common carrier terminal, its transmitting frequency (F3) was selected, in addition, a d.c. closure on the voice frequency line to the telephone exchange indicated to the operator the presence of a call request, or in the case of a dial office, returned a dial tone. A call was established and proceeded in the normal manner. When the call was terminated and the subscriber replaced the handset, the carrier frequency oscillator was turned off. The lack of a carrier on the power line released the receiver control relays at the common carrier terminal and returned it to its standby condition. The standby condition at the common carrier terminal provided a disconnecting signal at the telephone exchange.

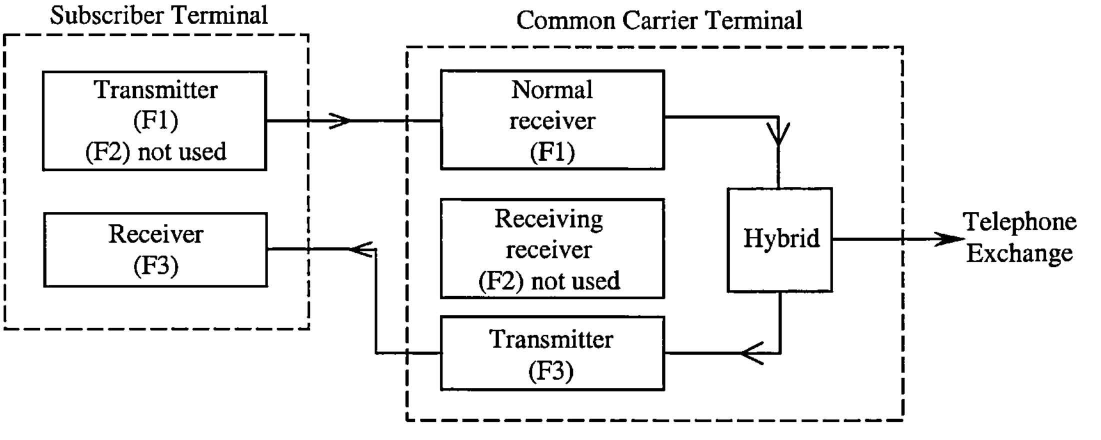


Figure 2.13: Subscriber to Common Carrier Terminal Connection

(2) For a call from a voice frequency subscriber to a carrier party, or from a carrier party to another carrier party on a different channel, the method of operation was as follows.

A call was made to the telephone exchange in the normal manner. At the telephone exchange, the called party's code ring was placed on the voice frequency line to the common carrier terminal. The code ring caused the transmitter to transmit a carrier at its frequency (F3), but pulsed at a rate of 30 Hz synchronised with the 60 Hz power supply. The particular phase of the 60 Hz power supply with which the pulses were synchronised depended on which of the two line relays, associated with the ringing control, was pulled up by the applied ringing power. Each subscriber telephone would respond to only one ringing phase, thereby providing limited divided code ringing.

When the called party lifted the handset, his transmitting oscillator was energised and a carrier frequency (F1) was returned to the common carrier terminal. The received carrier would disable the ringing control and establish a connection between the called and the calling parties.

When the call was terminated, the subscriber's handset was replaced, which would de-energise his transmitter. The lack of a carrier (F1) at the common carrier terminal caused its transmitter (F3) to closedown and its normal standby condition to be restored.

(3) For a call from one carrier subscriber to another carrier subscriber on the same channel (reverting call) the method of operation was as follows.

The calling party initiated a call in the same way as that described for (1). However once the number had been dialled, or the operator given the number, the handset was replaced thereby removing the carrier (F1) from the channel. Once the operator, or dial equipment, at the telephone exchange detected a free channel the called party's ring was placed on the line in the same way as that described for (2). When the called party lifted the handset his normal transmitting frequency (F1) was initiated, thereby indicating to the telephone exchange that the call had been answered. The transmitter at the common carrier terminal was placed in the operating condition at frequency (F3) as before. After hearing the code ring stop, the calling party lifted his handset for a second time, the frequency selector in the calling parties subscriber terminal selected the transmitter's reverting frequency (F2). This carrier frequency was detected at the common carrier terminal, which caused the reverting receiver control to operate. This connected the calling parties voice frequency output across the receiving branch of the hybrid.

Figure 2.14 shows the operation of a reverting call. When either party terminated a call, the remaining party reverted to, or remained on, the normal transmitting frequency (F1). The common terminal reverted back to its standby condition only when both parties had replaced their handset.

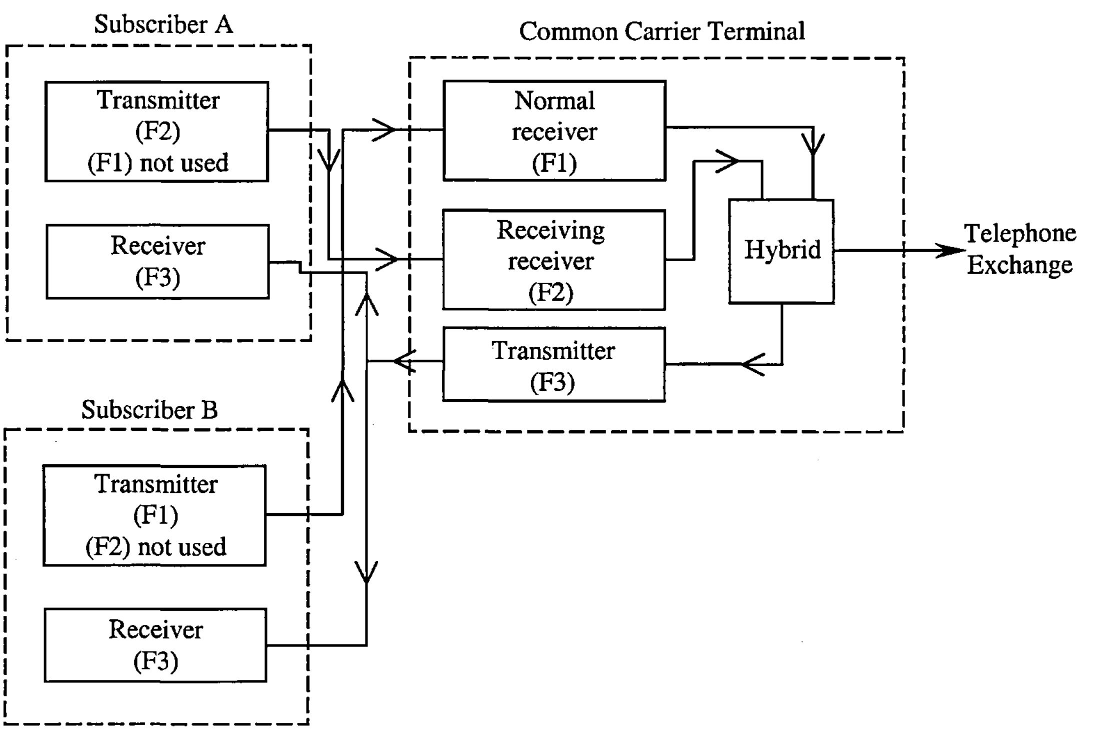


Figure 2.14: Reverting Call

2.4 Mainsborne Telecontrol from Thorn EMI

In the UK, Thorn EMI have been investigating the use of spread-spectrum, in the frequency range 20 kHz to 200 kHz, to facilitate bi-directional signalling on the low voltage mains network [2.6, 2.7, 2.8, 2.9]. Since the early 1980s a number of experimental tests have been run in domestic dwellings at sites in London and Milton Keynes.

Within the frequency range of interest, time-varying peaks and nulls were observed in the propagation characteristics of the low voltage mains network. This was mainly due to customers applying loads. This precluded the use of an optimum frequency for signalling purposes. It was also determined that any mains signalling system would have to operate efficiently in the presence of four main types of noise:

1) Large erratic impulses which determine system protection levels.
2) Transient bursts that occur for short periods.
3) Gaussian noise, which is the background noise level that any system has to live with.
4) Systematic noise caused by other telecontrol systems.

Any signalling system used must also be secure i.e. it should hide the data being sent so that unauthorised reception is not readily available.

In order to operate successfully with these network conditions, Thorn EMI chose to use a spread-spectrum format. The transmitted signal is broadband giving tolerance to narrowband channel effects and rapid recovery from noise impulses. The correlation properties of the codes are difficult to destroy this also gives some immunity to interference. Finally the code sequences used for transmitting the data is inherently secure.

The experimental system produced by Thorn EMI consists of three principal components:

1) A Central Controller which is situated in a local substation.
2) A Home Unit positioned in the customer's premises adjacent to the electricity meter.
3) A Customer Display that can be placed anywhere in the customer's home.

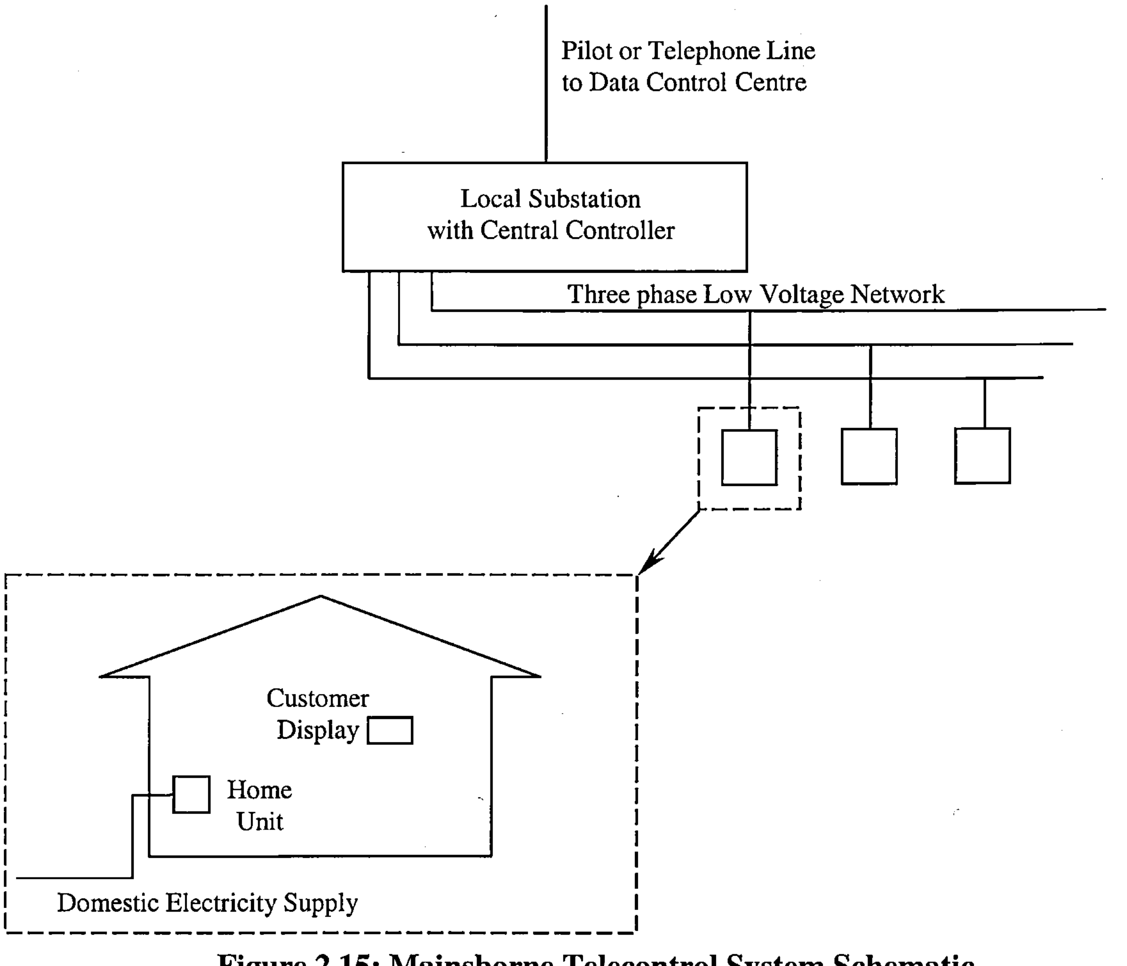


Figure 2.15: Mainsborne Telecontrol System Schematic

2.4.1 Central Controller

The central controller has the ability to communicate with up to 1024 home units using the low voltage network. Signal coding allows home units to be contacted individually, in groups or en masse. The central controller will send instructions to home units, respond to requests from home units and store data downloaded to it from home units.

The unit consists of five boards:

1) One microcomputer board is used for communications and facilitates local operational activities.
2) A second microcomputer board is a control board providing multi-tasking facilities.
3) The third board contains non-volatile memory storage for use in programmed activities.
4) The fourth board contains temporary storage pending filing instructions from the control board.
5) The fifth board contains the mainsborne communications interface and a clock calendar facility, enabling real time instructions from the controller to the home units. A rechargeable battery enables clock calendar operation in the event of a power failure.

A Data Control Centre has access to the central controller via a pilot wire or telephone line. A subset of the X25 protocol is used providing full duplex communication at 2400 baud. At the low voltage side of the substation the central controller communicates with the home units at 200 baud with a communicating power level in the order of 10 μW/Hz/phase.

Under normal operating conditions, the central controller polls each home unit at pre-set times, to read meters and clear statistical meter reading buffers. Any home unit can however initiate alert or interrupt messages requesting service. In addition, on request from the data control centre, a central controller will transmit instructions to, or seek data and status reports from, home units in accord with different levels of ascribed priorities.

2.4.2 Home Unit

The home unit contains a home module and a communications module. The home module records meter reading data and stores billing and budgetary information. It provides load management facilities and anti-tampering protection. In addition, equipment status monitoring is carried out and reported to the central controller.

The communications module provides the interface between the home module and the low voltage mains network. It also provides access to a telephone line enabling communication between the home unit and the central controller if the low voltage supply is interrupted or if interference over a long period prevents communication over the mains.

The home module can interface with impulsing electricity, gas and water meters for meter reading purposes. It incorporates separate 80 A and 25 A electro-mechanical contactors, enabling remote control of space and water heating. It contains its own stand-by battery allowing gas and water meter activities to be supported in the event of power failure.

2.4.3 Customer Display

The customer display unit gives customers access to electricity, gas and water usage information. It can provide charges incurred and forecast long-term charges. It also allows the customer to override automatic load switching times and to set up new times for switching space and water heating.

2.5 Remote Meter Reading, an Italian Perspective

Loads may be controlled by means of instruments at users' premises, for example, dual meter with clock for dual-band charging. However in order to be effective in load optimisation requirements, user devices must be capable of receiving control signals from a remote control centre. If remote devices are used, a data feedback channel is also required for monitoring purposes.

Field trials on an experimental low voltage network remote control system were started in 1987 by three Italian companies: Esacontrol, Italtel-SIT and Microelettronica [2.10]. The trials involved 163 low voltage users in the Genoa region. The purpose of the trials were to demonstrate the feasibility of the application using the low voltage network as a data transmission medium. The low voltage network was the chosen transmission medium since it naturally connects all users to be controlled. However it was realised that the low voltage network would provide a complex transmission medium in view of:

1) Its tree topology which varies with time.
2) The presence of at least two voltage levels separated by three-phase transformers.
3) The coexistence of different types of line on the same network (overhead conductors and cables with different cross-sections etc.).
4) The continuous variations in load impedance distributed throughout the network.

An experimental, electrical power, remote meter-reading system was developed by the Italian team. The experimental system consisted of the following:

1) Integrated meters (single and three-phase), containing a Peripheral Processing Unit (PPU), at the users' premises.
2) Central Processing Unit (CPU) at the medium/low voltage substation.

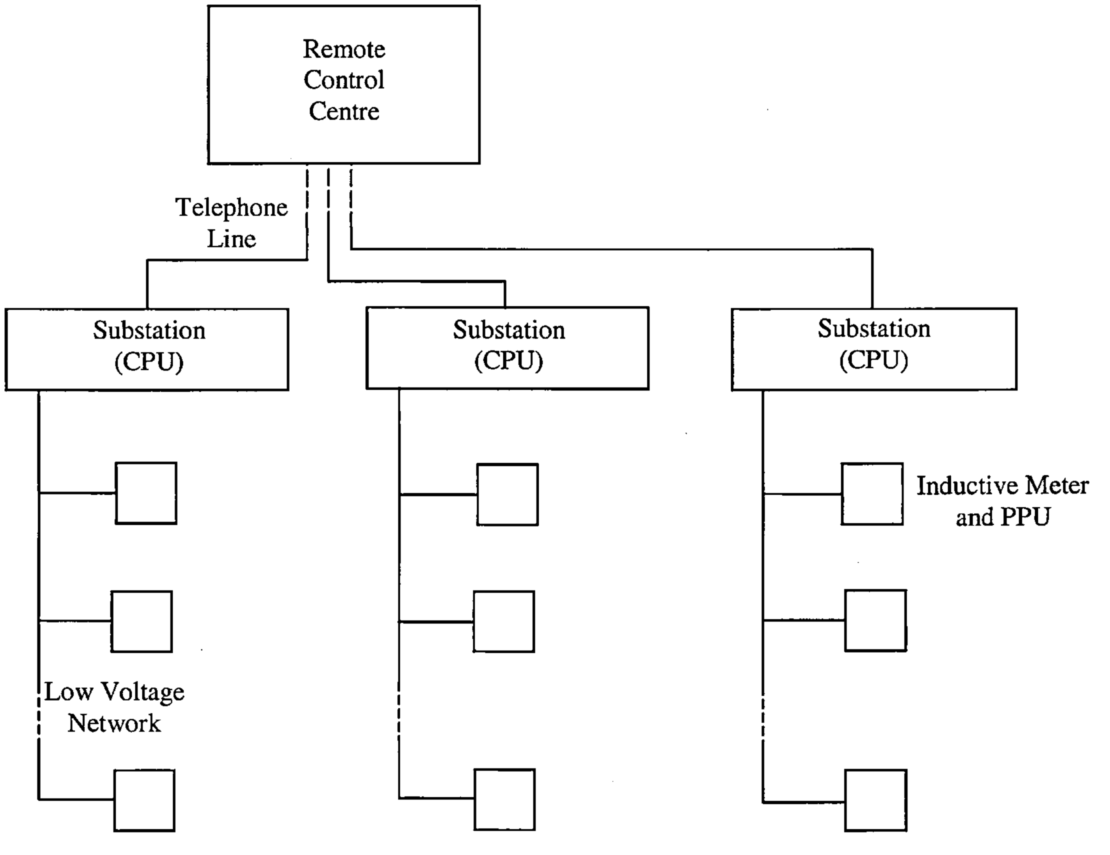


Figure 2.16: Remote Meter Reading System for Low Voltage Customers

The meters used are traditional rotating disc induction meters. An optical device "reads" the disc rotation, the data is processed locally by the PPU on the basis of operating parameters received from the CPU positioned in the substation. Processed data needed for invoicing and system monitoring is stored in the meter's memory and transmitted to the CPU on request.

The main tasks assigned to this remote meter reading system are as follows:

1) Frequent reading of consumption data for connected users.
2) Daily updating of different charge bands.
3) Power consumed by individual users is limited to a contractual value.
4) Peak power delivered during the month recorded.
5) Power consumed by all connected users (or meters) is limited, to help resolve critical conditions of availability.
6) Power delivered by the substation and the sum of the powers delivered to individual users is compared, to evaluate network losses.
7) Checking of parameters suitable for evaluating the state of the service and showing any attempted tampering.

The system was designed to ensure that charge data was fully protected against malfunction and deliberate attempts at alteration. It also had to be tolerant of all events connected with the network operation such as:

1) Interruptions in the supply.
2) Changes in the condition of a connection.
3) Electrical disturbance of considerable duration and intensity.
4) Variations in the number and characteristics of users.

These events may cause a connection between a PPU and CPU to be interrupted. However they do not lead to incorrect device operation or data loss.

The following design criteria were used for the development of the meter unit and PPU:

1) PPUs were given adequate intelligence to allow for long periods of autonomous operation, for example, when there are difficulties in communications.
2) The sum of all charge data and all parameters needed for operation are periodically updated and stored in non-volatile memory.
3) The ability to withstand interruptions in the supply, hold current operating data and restart automatically.
4) To calculate the amount by which the consumed power exceeds a reference value (during a two-minute period) and the consequent operation of a limiting switch.
5) The ability to identify the direction of rotation of the meter disc.
6) Consumption and maximum power figures corresponding to the previous month are kept for one month.
7) Control of local time base.
8) Validity checks on stored data.
9) Control of check registers permitting a remote control centre to show unauthorised changes in PPU operating parameters.
10) High self-diagnostic capability with remote control centre notified of results.
11) High degree of protection against overvoltages and conducted and induced interference.
12) Control of local serial port for connecting monitoring terminal or devices for extending to other services. Coupling to this port is possible without affecting the integrity of the meter cover.
13) Data to be transmitted on request using HDLC protocol.

14) Coupling between transmission system and low voltage line does not need to be adjusted in accordance with operating conditions.
15) Same procedure used for installing meters with PPU as for traditional meters. Local PPU operation begins automatically when a connection is made to a low voltage line.

At the substation the CPU is assigned the task of acquiring data and controlling the PPUs connected to the low voltage network. The following design criteria were used in order to achieve simplicity, efficiency and reliability of operation:

1) Centralised control of dialogues (polling).
2) Periodic interrogation of PPUs to keep operating parameters constantly under control.
3) Frequency of interrogation controlled in accordance with existing efficiency of connection.
4) Facility for transmitting control signals collectively (broadcast) or individually.
5) Control signals transmitted to alter charge band and freeze monthly consumption and energy balance data. Action deferred to permit all meters to be altered regardless of any temporary unavailability of the communication channel.
6) Checking that control signals are correctly received and take effect at the time established.
7) Contractual power limits and reduction coefficients for individual users are set by remote control to facilitate operations connected with user control.
8) Messages are considered correct by the HDLC protocol subject to syntactic analysis, in addition the sender's identity is also checked.
9) Consumption and control analysed for consistency.

10) PPU and CPU time bases constantly realigned.

11) New users brought on line using simple interactive procedure, and new meter operating parameters then automatically aligned.

12) Each change a centre makes to the operating parameters, or inconsistencies between known operating data at a centre and its peripheral equipment, is recorded and indicated.

13) Network condition is monitored by analysing meter responses.

The following criteria were used for the transmission system operating on the low voltage network:

1) A single time-shared transmission channel with polling, where the CPU acts as master.
2) Narrow-band transmission technique.
3) Transmission frequency around 100 kHz.
4) FSK modulation which permits relative circuit simplicity and integrability to be combined with good noise immunity.
5) Transmission rate of 600 baud for a good compromise between data transfer rate and signal bandwidth.

A communications protocol was developed in accordance with ISO/OSI recommendations and has the following functions:

1) The control of a multidrop network with a facility for individual and collective addressing.
2) Half-duplex transmission between master (CPU) and slave (PPU), with question/answer type data exchange with polling.
3) All data contained in a message of variable length with field structure.

4) Integrity of data guaranteed in a particularly disturbed transmission environment.

After examining specifications covering the frame structure and dialogue procedures the HDLC (High-level Data Link Control) protocol was chosen. This protocol is widely used, and is defined by the following aspects:

1) Availability of the chips controlling the protocol interface.
2) Bit-stuffing mechanism, included in hardware, which resolves the problem of data transparency in a simple way.
3) Good capability for detecting incorrect messages.
4) Facility for multidrop and broadcast route selection.
5) System and frame synchronism achieved with limited overhead.

For the trials, an underground section of three-phase low voltage line was made available by ENEL the Italian national electricity company. The line was approximately 530 metres long, excluding risers in buildings, and supplied some 163 users (147 single-phase and 16 three-phase). The users included workshops, houses and flats (one containing thirteen floors). Extensive testing was carried out on the line to determine attenuation, noise, line impedance and crosstalk between phases. The results generally confirmed trends already pointed out in literature, apart from attenuation, which varied considerably with time.

Once fully installed, system performance was checked under various normal and abnormal operating conditions, on the low voltage network. Results obtained during the first few months confirmed the technical and operating feasibility of a remote control and meter reading system where the network itself was used as a communications medium.

2.6 Datawatt's Robcom system

The Robcom (Robust Communication) research project investigated the medium and low voltage distribution networks in the late 1980s and early 1990s. The aim being to develop a two-way communication system for use by electricity utilities over their own distribution networks [2.11, 2.12]. A communication link between a central control station and those points in the network where measurements have to be collected, for example meter reading, or commands have to be received, for example circuit breakers and remote load control, facilitates a more efficient power supply system.

Following CENELEC's standard EN 50065, Robcom used the frequency bands 3 to 95 kHz for data communication. Below 20 kHz the noise on the network is dominated by power signal harmonics, this makes efficient data communication with low transmit power at a reasonable data rate very difficult. In addition, low signal attenuation through the transformers would result in mutual interference between different parts of the network.

Above 20 kHz the noise on the distribution network results from loads such as motors, TV sets and other electrical equipment with power signal harmonics no longer dominant. Signal attenuation through the transformer is now significant and neighbouring parts of the network no longer interfere with each other. In addition, loads as well as the topology of the distribution network also affect signal attenuation. This leads to a large variation in received signal quality as a function of frequency, time and location. The Robcom system uses the frequency band between 20 and 90 kHz.

Due to the unpredictable variation in network characteristics, frequency hopping spread spectrum was chosen as the signal transmission technique. Typically 20 different frequencies are used sequentially to transmit the data. A frequency cycle lasts for half a second, therefore any one frequency is only used for 25 milliseconds in any cycle. See figure 2.17.

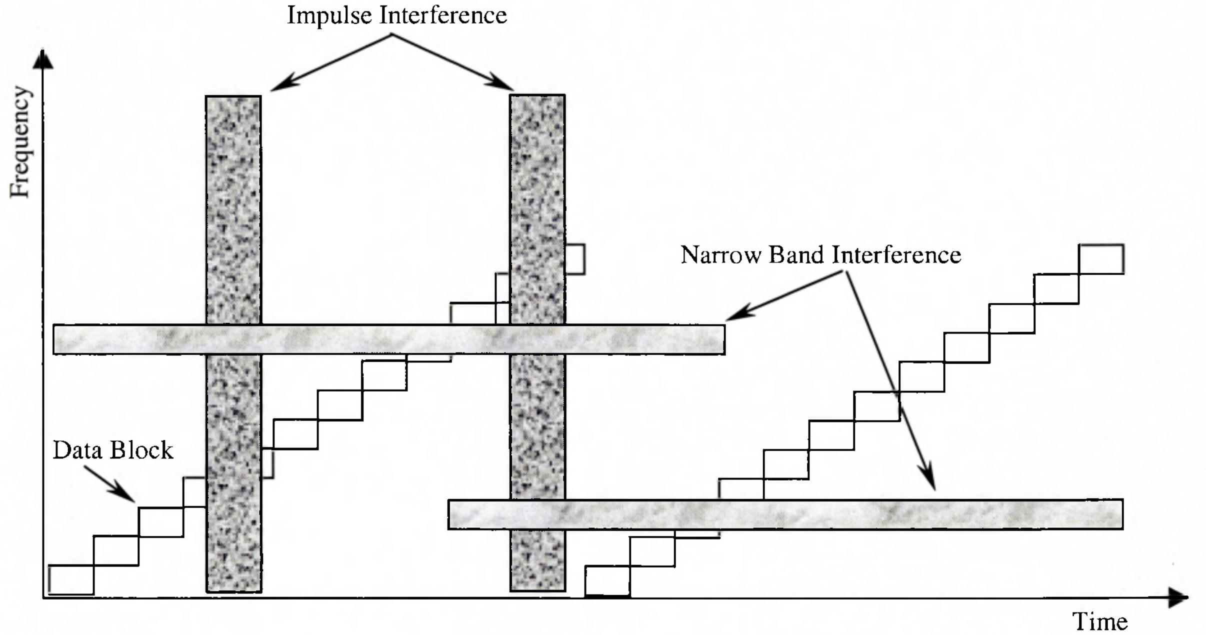


Figure 2.17: Frequency Hopping and the effect of Interference

Transmission errors are unavoidable therefore error detection and correction measures had to be built into the system. In order to provide an error correction capability it is necessary to add redundancy to the data package before transmission. In the Robcom system this approximately doubles the amount of data that is sent through the channel. This reduces the need for retransmissions and increases the basic distance that can be covered between two stations without using any repeating. Error detection is used to detect any residual errors in which case a retransmission is requested. This provides a probability of less than 10^{-12} for accepting an erroneous telegram as correct. The Robcom system uses a data rate of 1000 bits per second.

A maximum output power of half a watt is used to transmit the data. Despite the limited transmit power, large distances can be covered using any one of the installed stations as intelligent repeater stations. The same concept is also used to ensure good quality reception on varying network topologies and changing channel characteristics.

The data exchange protocol used by Robcom detects any topological or channel changes and automatically adapts the logical structure of the data network. Therefore the choice of the most efficient data transmission path and suitable repeater stations is constantly monitored and updated. In addition, the protocol also controls the search for new stations and their inclusion within the data network.

2.6.1 Robcom Network Hierarchy

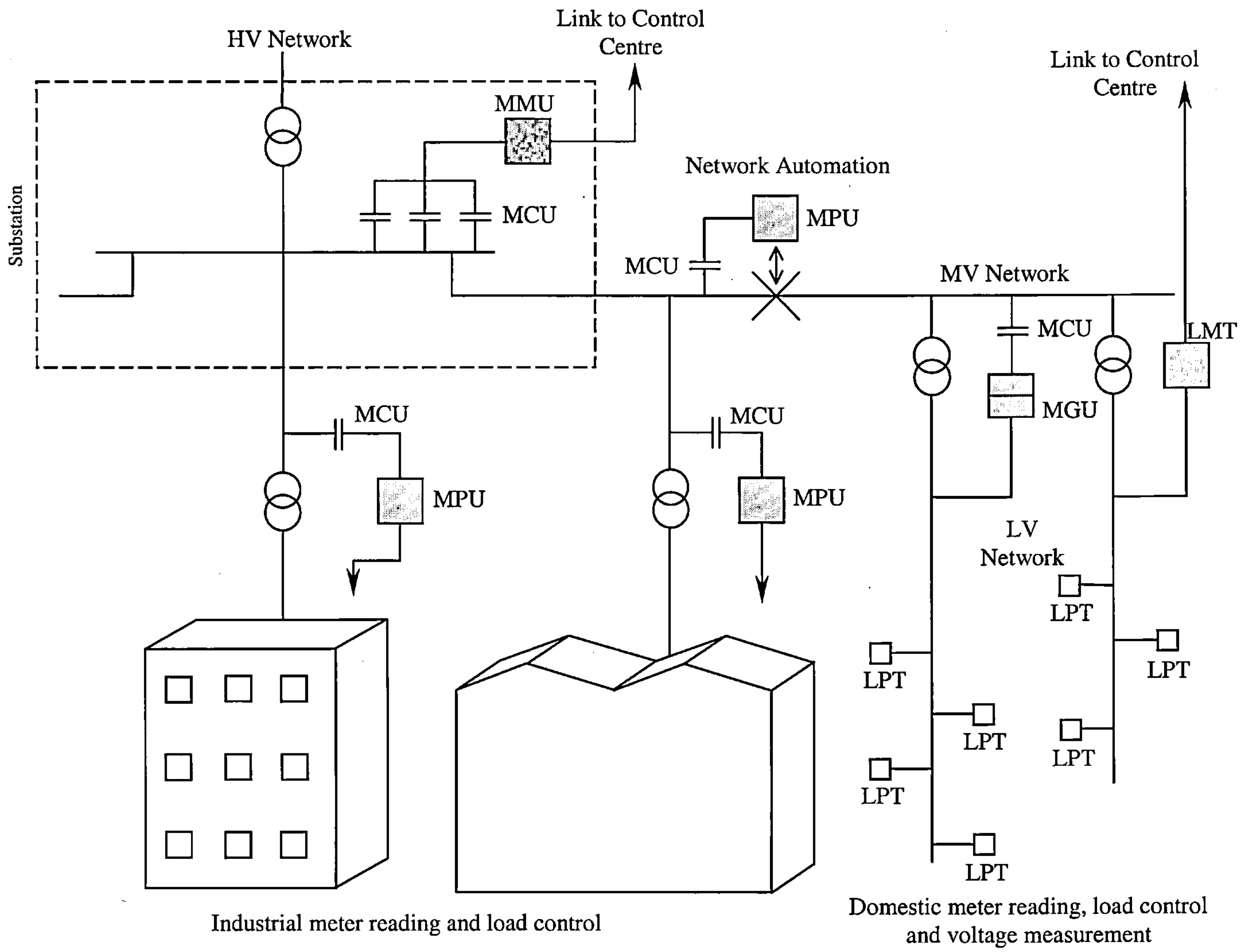


Figure 2.18: The Robcom Network

2.6.2 Control Centre

The control centre is responsible for issuing commands, collecting and storing metering and operational data and maintaining a real-time data base. Communication between control centre and substation takes place over conventional media such as pilot wires, telephone links, microwave channels and optical fibres.

2.6.3 Medium Voltage Equipment

2.6.3.1 Medium Voltage Master Unit (MMU)

The MMU consists of a master terminal, a modem for communication with the control centre and a coupling filter.

The MMU is responsible for all the network management functions on the medium voltage network. It communicates with all the installed slave units on the medium voltage network and automatically integrates new stations into the network. The MMU continuously checks the well-being of all the slave stations and determines the best routing strategy within the network.

2.6.3.2 Medium Voltage Process Control Unit (MPU)

The MPU consists of a master terminal and a coupling filter for connection to the medium voltage line.

MPUs are used as process control terminals and are positioned at desired points throughout the medium voltage distribution network. The terminal contains six mono-stable relays, allowing the control of six external elements such as remotely controlled breakers. Four serial interfaces are available to communicate with up to four external devices using either RS232 or 20 mA loop standards. Eight binary inputs are provided for monitoring potential-free external contacts. These inputs can also be used to count pulses from meters equipped with pulse interfaces. Finally five analog inputs can be used for acquisition of voltage, current and load measurements.

2.6.3.3 Medium Voltage Gateway Units (MGU)

The MGU consists of a gateway terminal a coupling filter and a low voltage master terminal.

MGUs are used to divert signals around the distribution transformers from the medium to the low voltage networks and vice versa. In addition it can also be used as an MPU. The only difference being the number of serial interfaces available to the user, as one interface is reserved for interconnection between the gateway terminal and the low voltage master terminal.

2.6.3.4 Medium Voltage Coupling Unit (MCU)

The MCU consists of a medium voltage coupling capacitor and a primary over-voltage protection device.

MCUs are employed to couple the signal into and out of the medium voltage power lines. One or more of these units are used to couple a medium voltage communication unit to the power lines.

2.6.4 Low Voltage Equipment

2.6.4.1 Low Voltage Master Terminal (LMT)

The LMT is functionally identical to the medium voltage master terminal contained within the MMU.

The LMT is responsible for all the network management functions on the medium voltage network. It communicates downstream with all the installed slave units on the low voltage network. Upstream it communicates either directly with the host computer in the control centre or with a medium voltage gateway terminal. It continually checks the well-being of all the slave stations, integrates new stations into the network and determines the best routing strategy within the network.

2.6.4.2 Low Voltage Process Control Terminal (LPT)

The LPT is functionally identical to the medium voltage process control terminal.

LPTs are used as process control terminals and are positioned at desired points throughout the low voltage distribution network. The terminal contains six bi-stable relays for carrying out load management functions such as: direct load control, tariff switching, control of hot water heaters and space heaters. Four serial interfaces are available to communicate with up to four external devices using either RS232 or 20 mA loop standards. Eight binary inputs are provided for monitoring potential-free external contacts. These inputs can also be used to count pulses from meters equipped with pulse interfaces. Finally five analog inputs can be used for acquisition of voltage, current and load measurements.

2.6.5 Customer Display Unit

A customer display unit is available which can be connected to any power socket in the house. Text messages can be sent over the household wiring, advising consumers on energy use and special tariffs.

2.6.6 Performance Testing

The Robcom system has been tested on a variety of networks within Europe. Early low voltage tests were undertaken in Untersiggenthal, Switzerland and Wolvega, in the Netherlands. A pilot installation has been established in Geneva on both the medium and low voltage networks. Tests on overhead lines have been carried out at a training network in Ottmarsheim. Signal propagation tests have also been performed on medium and low voltage networks in Den Haag and Amsterdam in the Netherlands.

2.6.6.1 Medium Voltage Underground Cables

Cable lengths of up to 7 km have been successfully tested. With a maximum transmit power of half a watt, no repeater stations were required to reach even the most remote stations from a master in a substation. Crosstalk was found to be significant, therefore the signal is coupled to a single phase whilst remote stations are coupled to any phase.

2.6.6.2 Medium Voltage Overhead Cables

The tests on overhead cables were restricted to a 3.5 km long network at Ottmarsheim. It was therefore difficult to predict signal propagation characteristics over greater distances. However, results obtained show little signal attenuation over most of the frequency band of interest.

2.6.6.3 Mixed Medium Voltage Networks

Networks containing both underground and overhead cables were found to suffer from problems resulting from the impedance mismatch. It was observed that little power is transferred from an underground cable network onto overhead lines. Large losses are also experienced at points where an underground cable branches off from an overhead line. A single repeater station installed in the overhead network proved sufficient to successfully combat this problem.

2.6.6.4 Low Voltage Networks

From results obtained in The Netherlands, a rule of thumb was derived for the low voltage network. It was found that one low voltage master unit could successfully communicate with all slave units within a radius of 200 meters. This gave coverage of 0.125 km^2 without a repeater level. With one repeater level a master unit can cover an area of 0.5 km^2 and if 2 repeater levels are used, the area is increased to 1.13 km^2.

2.7 Siemens Remote Meter Reading System

Siemens realised that a system only offering remote meter reading facilities was unlikely to be cost effective [2.13]. However, when this was linked with additional features such as load management, load profile recording, half hourly meter reading, remote disconnection and re-connection, credit control and an effective means of detecting fraud, revenue loss could be significantly reduced.

Although the electricity distribution network was chosen for the communications media, all the alternatives were investigated and the conclusions were as follows:

2.7.1 Idle-Line Working

An Idle-Line working telephone call, once a quarter to each consumer for meter reading is practical, but potentially simultaneous calls to more than a million consumers in each region on the telephone network would be impractical and costly. Telephone connections are rarely located adjacent to the electricity meter, therefore additional wiring would be required. In addition, telephone coverage is not universal, especially in areas where pre-payment and fraud detection may be required. Finally, pricing policy on the part of the telephone companies may rule out large-scale use of Idle-Line working.

2.7.2 Radio

With personal communication networks, cellular telephones and dedicated systems, radio is another option. No routing of wires is required, therefore reducing the installation costs. However, if the call charges for today's cellular telephones are any guide to future pricing, they are unlikely to be cost-effective. Bandwidth limitations would cause serious difficulties in implementing a large-scale system. In addition, radio communications are relatively easy to listen in to and hence tamper with.

2.7.3 Cable TV

Cable TV networks are another possibility, however they have limited coverage, especially outside urban areas and once again there is the expense of wiring to the meter.

2.7.4 Power Line

2.7.4.1 Disadvantages

The electricity distribution network is not an ideal communications medium. Network impedance varies; signal attenuation and noise levels also vary with demand. There can be significant differences in network characteristics across the frequency band.

2.7.4.2 Advantages

The electricity distribution network goes to every electricity consumer and the connection point is at the meter. There are no extra costs due to the installation of additional wiring. Bandwidth is comparatively freely available and communications are less easy to listen in to and tamper with. In addition there are no rental costs due to another network operator, for example, telephone or cable TV companies.

2.7.5 Modulation Technique

Siemens opted for a frequency-agile, narrow band, coherent carrier system with orthogonal phase modulation. The system was implemented using low power, CMOS semi-custom cellular technology on a single integrated circuit. Figure 2.19 shows a block diagram of the chip which Siemens call a Phase Space Processor.

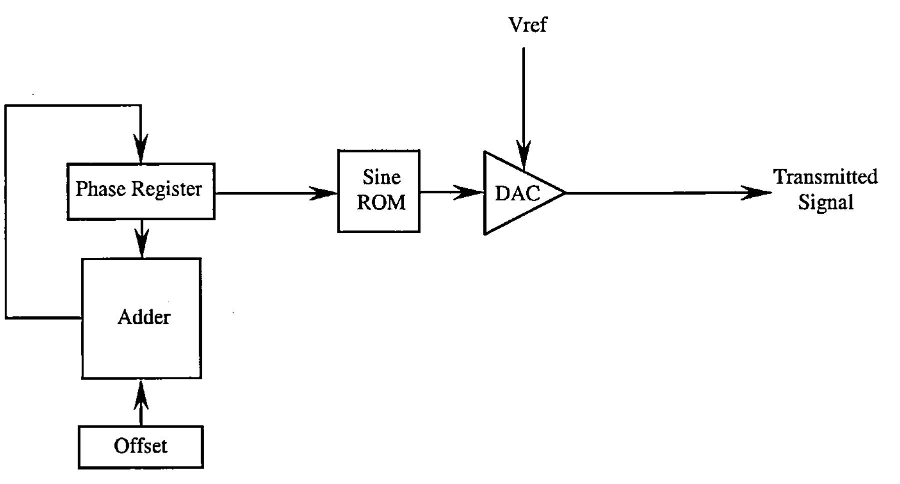


Figure 2.19: Phase Space Processor

The phase register holds a representation of the carrier signal in terms of its instantaneous phase angle. A small offset is added to the phase register approximately every microsecond; this generates a continuously rotating phase vector. The phase angle is converted to an amplitude via a sine look-up table and then into a carrier frequency by the digital-to-analogue converter (DAC). Modulating the carrier involves adding a larger number to the phase register at the start of each of the transmitted data bits.

The frequency of the carrier can be altered by changing the offset added to the phase register each cycle. This provides frequency-agility and allows noisy parts of the frequency band to be avoided.

For signal reception, adding a second phase register to generate a quadrature signal, feeding the received signal into the reference input of the digital-to-analogue converter, which acts as a mixer, and sampling the output with an analogue to digital converter allows the phase space processor to become a phase-lock loop with the offset number being fine-tuned to ensure that the system phase-locks to the incoming signal.

This technique provides a reliable communications system, even in very noisy environments and is particularly resistant to impulse noise which is characteristic of the mains environment.

2.7.6 System Structure

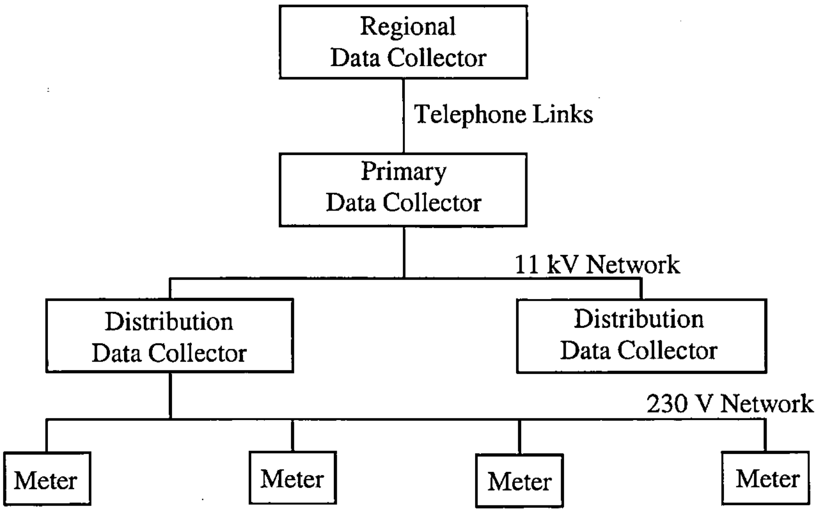


Figure 2.20: Mains Metering System Structure

2.7.6.1 The Meter

The operating software required by the meter is downloaded from the Distribution Data Collector (DDC). Once installed, only occasional messages from the DDC are required for time synchronisation or tariff amendments.

The meter is an 8 rate unit with maximum demand capability and switching times controlled by time of day, day of the week and season, plus holiday exceptions. The meter is also capable of providing a half-hourly load profile. It can have a primary load contactor for remote disconnection and pre-payment applications plus additional 80 A and 25 A load contactors. Various fraud measures such as reverse current and cover removal are automatically detected and reported back to the Regional Data Collector.

A customer display on the meter gives information such as time, date, consumption, cost of electricity used and next bill projection. An external customer display is also available.

2.7.6.2 Distributlon Data Collection (DDC)

A Distribution Data Collector is located in the low voltage substation. It continually polls all the meters on the low voltage network, collects and stores data from them and sends data to them as required. The DDC also detects the presence of new meters and automatically logs them onto the network.

If direct contact between DDC and meter is not possible, the DDC automatically determines the need for repeaters. All meters are capable of acting as repeaters and the DDC allocates repeater duties as required.

A typical low voltage network may have 200 to 300 meters; a DDC however can manage 1000 meters under normal conditions and up to 2000 meters under emergency conditions.

2.7.6.3 Primary Data Collector

The medium voltage, electricity distribution network is the preferred communication media connecting the DDCs to the primary substations, where telecommunication links usually exist. A Primary Data Collector is located at the primary substation, which acts as a store and forward device, switching data messages between the DDCs and the Regional Data Collector.

The final three case studies highlight some alternative technologies developed over the past twenty years.

2.8 Radio Teleswitching

In 1979, trials began on a technique for remote load control and tariff switching called Radio Teleswitching. The project required the collaboration of the Electricity Supply industry, meter manufactures and the British Broadcasting Corporation. The BBC's 198 kHz long-wave transmitters were used to send coded signals to a small receiver fitted beside the electricity meter. The received signal activated switches which controlled multi-rate tariff meters, space heating and water heating [2.14, 2.15, 2.16].

Radio Teleswitching is a one-way communication system which employs phase-modulation of the BBC's 198 kHz long-wave signal. This frequency is used for BBC radio 4 broadcasts during the day and the BBC World Service during the early hours of the morning. Three 198 kHz transmitters are used to cover the whole of Great Britain and are sited at Droitwich (covering England and Wales), Westerglen (covering southern Scotland) and Burghead (covering northern Scotland).

Information is added to the radio broadcast in a similar way that teletext is added to the television signal. One pre-requisite was that the modulation technique used should not affect normal programme reception. Tests established phase modulation as the most suitable modulation technique to carry the data signals. This technique promised a wide coverage area and, with care, no interference to the normal programme transmission. A possible problem arose in the fringe areas of the long-wave transmitters. The received r.f. signal is the vector sum of the ground-wave and sky-wave signals. Both signals are identically phase-modulated by the data signal. However the sky-wave is delayed relative to the ground-wave. Due to this difference in timing, modulation of the phase-difference between the two components takes place and this causes audible amplitude-modulation by the data signal of the resultant received carrier, shown in figure 2.21. In order to minimise this effect, both the phase-deviation and the data bit-rate are kept relatively low. Experimental results revealed that little interference, even in the worst reception areas, resulted if a phase-deviation of 25° and a data rate of 25 bits per second were used.

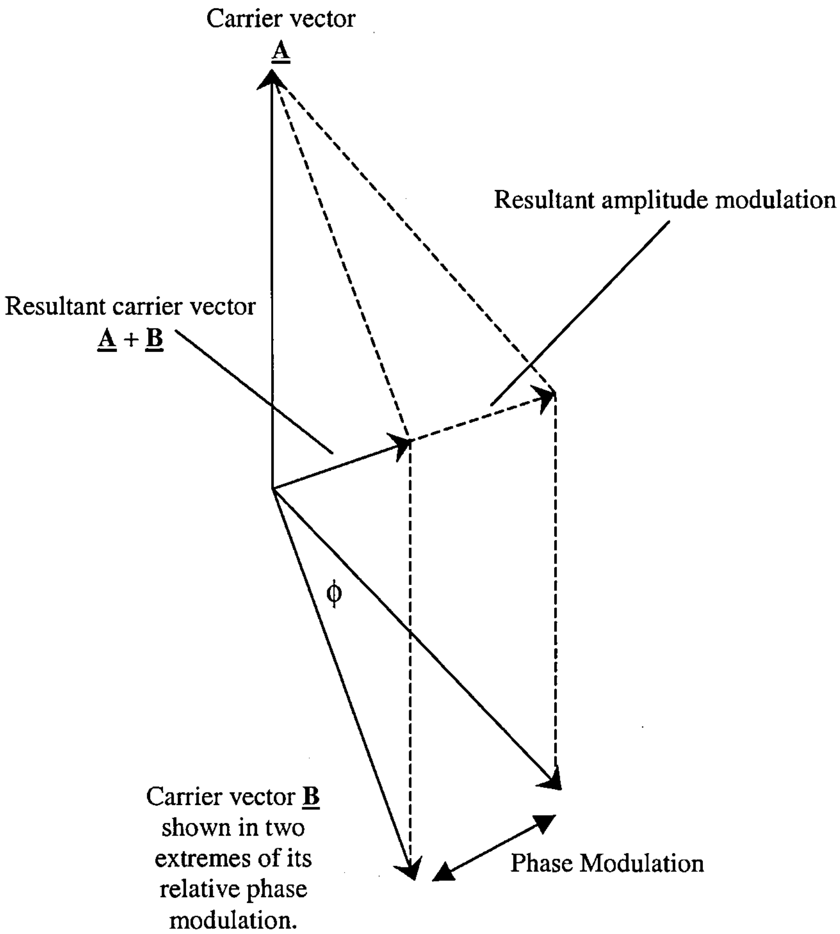


Figure 2.21: Amplitude Modulation resulting from Phase Modulation

A synchronous data system was chosen and the data and frame structure is as follows: A data '1' is indicated by a phase advance of 25° for 20 ms followed by a phase retard of 25° for 20 ms. A data '0' is indicated by a phase retard of 25° for 20 ms followed by a phase advance of 25° for 20 ms. Data is sent in frames of 50 data bits, each frame taking two seconds to broadcast. Frames are made up of a synchronising prefix set at '1', a four bit application code, a 32 bit message and a 13 bit check word.

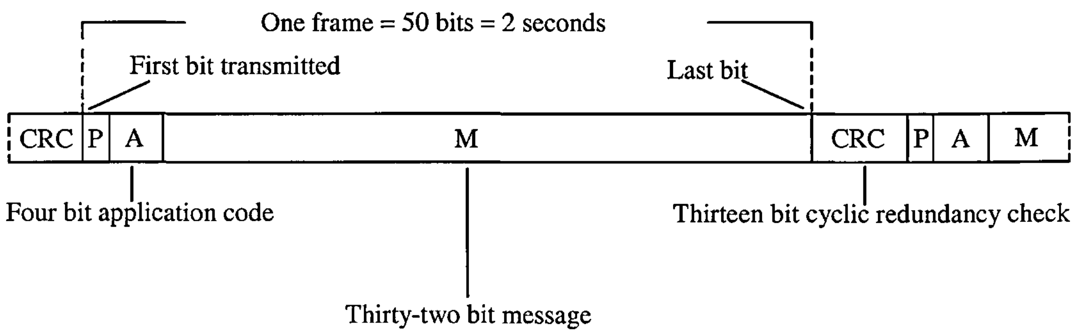


Figure 2.22: Frame Structure

All Area Boards switching instructions are sent to a Central Teleswitching Control Unit (CTCU) via a normal data telephone link. The CTCU arranges all the instructions and passes them to the BBC for broadcasting. The CTCU also holds a seven-day programme for each Area Board and these are automatically sent to the BBC when needed. Each Area Board was allocated a Board code and each teleswitch purchased can only receive codes initiated by that Board.

A number of other services are also offered by the BBC on the 198 kHz signal, for example, a time code signal and a weather information system. Therefore all messages to be transmitted are assembled and given an order of priority at Broadcasting House in London.

Both 'immediate' and 'programme' commands can be broadcast. Programme commands are broadcast in advance of the switching time and give an 'ON time' and an 'ON period'. Immediate commands can be broadcast if a Board requires a group of customers to be switched immediately. The Area Board requiring an immediate command sends the command to the CTCU which in turn sends it to the BBC for broadcasting in the high priority queue.

The radio teleswitch, located next to the electricity meter, consists of a radio receiver and a microprocessor for data decoding and output switch control. Two switches are provided for tariff purposes and two for load switching. The unit holds a 24-hour programme for each switch, up to four ON times and ON periods can be specified for each switch. In the event of a power supply failure to the radio teleswitch, all programme instructions will be lost. However, during this time the meter will revert back to Economy 7 times until the next update is broadcast. A teleswitch does not control more than 100 MW and there are no master codes, thereby limiting the effects of a wrong code.

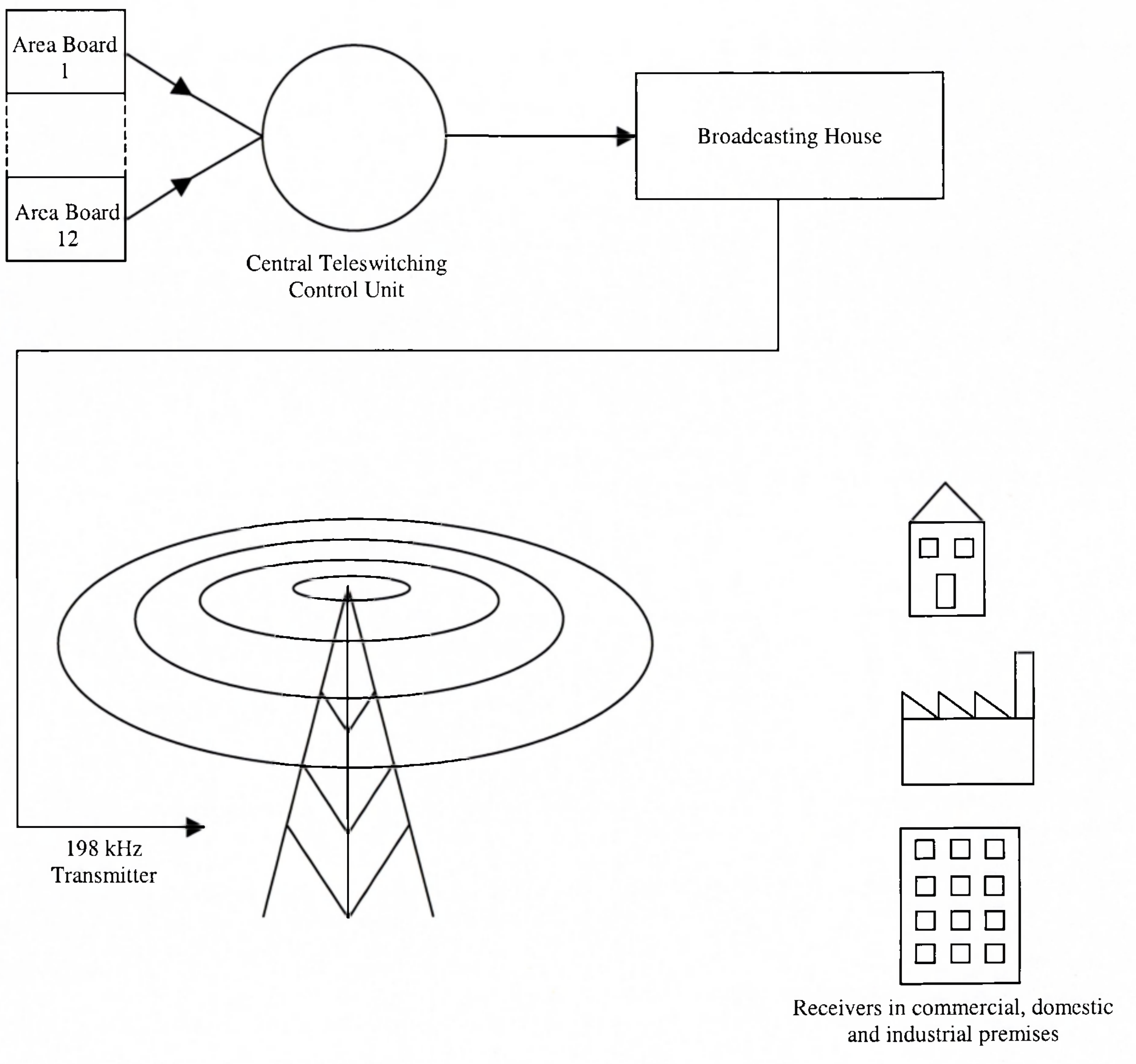


Figure 2.23: Radio Teleswitch, chain of communication

2.9 Idle-Line Working (Telephone Interrogation)

The telephone network can be used to transfer metering and load control data between an intelligent meter and a data collection centre. The technique known as Idle-Line Working allows a remote unit to be interrogated via a normal telephone line without generating a ring current [2.17, 2.18]. The householder remains unaware of the system being in use, allowing data collection at times when the telephone is unlikely to be required, for example in the early hours of the morning. The network is constantly monitored for incoming and outgoing calls that take precedence. In the event of a call request during data transfer, communications between the data collection centre and the remote unit is immediately discontinued allowing normal telephone operation. Data transfer is resumed at a later time when the line is once again free. One system which offers Idle-Line Working as a possible alternative to PLC is the Credit And Load Management System (CALMS).

2.9.1 Credit And Load Management System (CALMS)

In the early 1980s the South Eastern Electricity Board developed a comprehensive credit and load management system [2.19]. It was envisaged that a system such as CALMS would enable the utility to make better use of its resources and the customer to monitor the cost of their electricity, possibly modifying their usage patterns to benefit from new tariff structures. At the customer's premises, a microelectronic unit (CALMU) replaced the electricity meter and time-switch. A communication system provided real-time duplex communication between the CALMUs and the electricity board's accounting and engineering control networks.

The perceived benefits from such a system included:

1) Measurement and recording of demand and maximum demand.
2) Remotely selectable tariff arrangements from a range of pre-programmed options.
3) Calculation of outstanding charges for continuous display to the customer.
4) Provision of electrical loading and demand information to assist in network planning and control.
5) Ability to institute tariff and price revisions remotely at a given date and time.
6) Remote reading of a 3-rate meter.
7) Acceptance of customer payments remotely via the CALMU.
8) Presentation of a range of information to the customer via a touch panel and display on the CALMU.
9) Provision of enhanced tariff types incorporating time-switching of customer-selected appliances.
10) Application of load limits for use in tariffs or in system emergencies as an alternative to rota disconnections.
11) Metering and accounting for gas and water utilities using inputs from metering sensors.
12) Earth leakage protection facilities at customers' premises.

The CALMU consists of two units, shown in figure 2.24: the mains unit or meter and a touch panel to enable customer interaction.

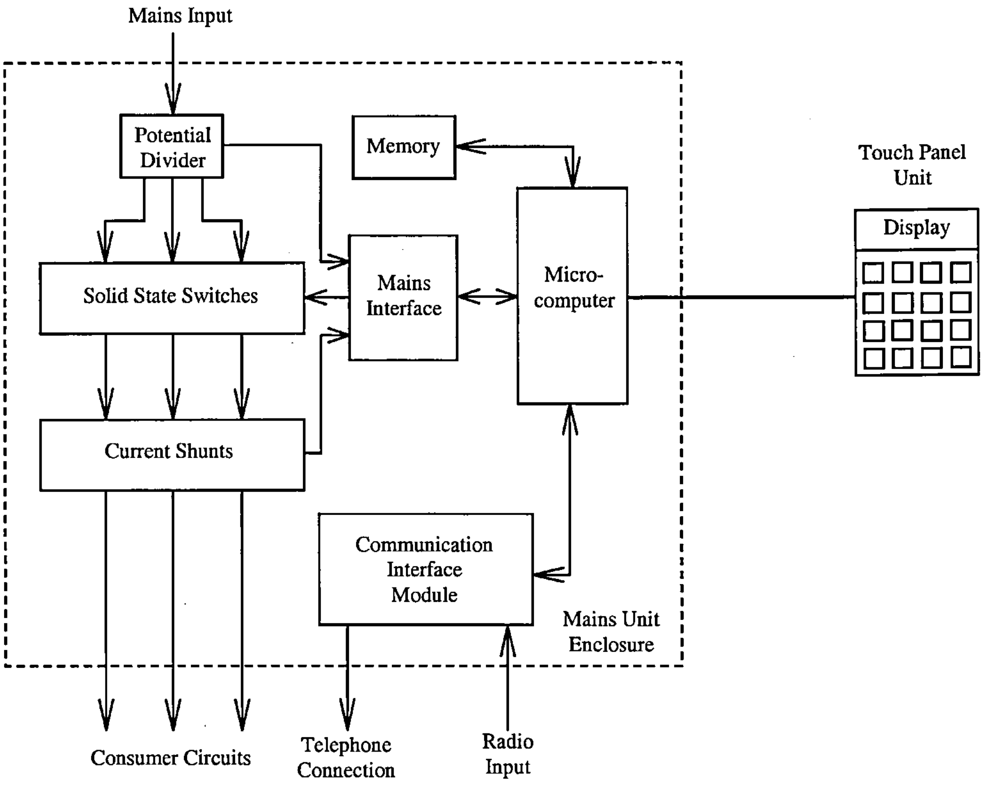


Figure 2.24: CALMU – Schematic Diagram

2.9.2 Mains Unit Enclosure

The mains unit enclosure replaces the electricity meter. Solid state electronics are used to record electricity usage. A sample low voltage representation of the mains voltage and current are used to determine usage. A resistive potential divider is employed for the voltage and a low value shunt with an amplifier is used for the current. The meters are designed for an accuracy of better than ± 1% in the full range 1 to 100 Ampères on each metered circuit. At regular intervals, the accumulated sample totals for voltage and in-phase current are transferred to non-volatile memory. An Intel 8022 single-chip microcomputer, one of two utilised in the mains unit, uses the voltage and current information to calculate demand, maximum demand and outstanding charges for display to the consumer if required. The unit also includes self-checking and remote-monitoring techniques to increase the reliability of the measurement.

Three separate switchable customer circuits were incorporated for load management purposes. Switching was accomplished using solid-state triac switches. Although this introduced an unavoidable energy loss, due to the barrier forward voltage drop, this only amounts to approximately 0.4% of the through energy. This loss is offset against high reliability and the ability to use the triac's high speed switching to introduce coded signalling for control of selected customer apparatus.

2.9.3 Touch Panel Unit

The customer display and touch panel is placed in a convenient position inside the customer's premises. It is used to:

1) Display information such as meter readings, estimated cost of electricity used and time.
2) Give warnings of abnormal supply such as earth faults.
3) Pre-programme customer options such as time-switching of selected appliances.

2.9.4 Data Concentrator

A data concentrator is located at a substation or a telephone exchange, depending on the communication technique used. Each data concentrator acts as a message-routing device and constantly scans the network, polling each CALMU for a list of status flags. A single data concentrator can maintain up to 10,000 CALMUs though numbers substantially less than this are more likely. The polling routine is undertaken on an hourly basis and a data rate of 300 bits per second is used over the communications medium.

The system was designed to be, as far as possible, independent of the choice of communication medium. PLC or telephone Idle-Line Working can be used. These systems can also be supplemented by the use of radio teleswitching.

In turn, the data concentrator is polled by the utility's communication system. Usage information is passed back to the utility offices whilst load management commands, such as switching instructions for water and space heaters, are sent to each CALMU via the data concentrators. The communication links between the data concentrators and the utility offices operate in full duplex mode at 9600 bits per second.

2.10 Remote Meter Reading using Simplex Radio Transmission

In February 1993, large scale trials began on the TANGENT radio automatic meter reading system [2.20, 2.21]. South Wales Electricity Company (SWALEC) and the meter manufacturer Schlumberger undertook these trials. The system employed one-way radio transmission from the meter to a data concentrator using narrow-band techniques centred on 184 MHz. All the information collected was accessible from a desktop personal computer.

Early remote meter reading trials using radio in the UK closely followed the developments in the US and utilised the spectrum in the 900 MHz region. Although the trials were successful, the frequencies utilised were also used by analogue cellular phone systems and the European GSM (Global System for Mobile communications) system. However, in 1982, VHF television broadcasting was discontinued in the UK, making available the frequencies between 174 MHz and 225 MHz. Much of this band was re-allocated to mobile radio use. France and the Republic of Ireland on the other hand still use VHF television broadcasting. Therefore in order not to interfere with their signals, some sensitive parts of the VHF band were not allocated for high power use. The UK Radio Communications Agency allocated one of these sensitive segments, in-between 183.5 MHz and 184.5 MHz, to the utilities for the purpose of automatic meter reading. Transmitters using this frequency band are restricted to a transmit power not exceeding 10 milliwatts.

The TANGENT meter is a five-rate watt hour meter with an internal real time clock. It can be read and programmed via an optical port. The meter includes a radio transmitter and an antenna accommodated within the meter case. An 18-byte packet of data is transmitted each time 100 watt hours of energy use is recorded. The meter is programmed never to transmit more than once every 15 minutes; this helps limit channel congestion during periods of high use. Data is transmitted at 1200 bits per second using FSK modulation.

The transmitted data is received at either a data concentrator or a radio repeater. The repeater relays all metering information to the nearest concentrator site. A data concentrator consists of two antennas and radio receivers, a data packet decoder, a computer with a hard disk store and a CCITT V32 modem.

Under normal conditions, a data packet will be received on both receivers. However, in certain cases the characteristics of the radio channel are such that a packet will only be received on one receiver, or different packets will be received on both receivers simultaneously. This receiver arrangement can reduce the effect of multipath radio propagation. Using a transmit power of 10 milliwatts an effective range of greater than 700 metres is achievable.

The sites chosen for the data concentrators were examples of urban, valley and rural areas. At St. Arvans near Chepstow, the data concentrator was placed inside a high voltage substation located on a hill overlooking the village. This data concentrator serves 28 meters. At Energlyn a small sub-urban area neighbouring Caerphilly, the data concentrator is again placed inside a high voltage substation located on a hill overlooking the town. This data concentrator serves 723 meters. The final data concentrator serves the Rhondda Valley and is located inside the SWALEC equipment room at the Penrhys telecommunications station. This data concentrator serves 246 meters.

The results obtained are stored on computer and from this information a range of reports can be generated. The simplest report lists all the installed meters and their last reading on a particular day. It is also possible to generate load profiles of energy use throughout the day, display meters with alarm states, observe packet success rate and check interference and signal strength.

The new meters were installed alongside the consumer's existing meter. Both meters were regularly read manually and the readings compared with each other and with the readings received at the network management centre via the data concentrator. As a result, the new meters and the radio transmission system were determined to be 100% accurate.

Most of the test meters were installed in external meter boxes to allow easy access for meter reading purposes during the testing stage. However, in reality, meters are installed in various locations both inside and outside the house, depending on age and type of property. Test results indicate that the difference in path loss between meters installed inside and outside the house are less than expected.

Co-channel interference from French television transmissions has been experienced. TV transmitters at Niort use the frequency 183.958 MHz as a vision carrier. This is potentially disruptive to the remote meter reading trials, which operate on 183.9625 MHz. Disturbances were plotted throughout 1993 and results indicate that disturbed conditions persist for less than four hours per month.

Chapter two introduced some of the key players and outlined some of the significant developments in Power Line Communications over the past seventy years. The next chapter will look in more detail at the problems associated with transmitting high frequency signals over cables designed for transporting low frequency a.c. power. Signal attenuation, noise, signal reflection and radiation, all have to be accounted for when designing a communication system utilising the power network.

The rest of this thesis is devoted to an investigation of the UK's Low Voltage Distribution network; no work on Medium or High voltage systems is included. It must be borne in mind that although the principles for delivering power to the home or factory is the same the world over, the implementation can be very different. Having worked on Low Voltage Distribution networks throughout Europe and having had experience of networks in America, Australia and the Pacific Rim, the author has not encountered two identical systems. Although much of Europe shares a similar voltage level, 230 V, and three-phase distribution, usually underground, each country implements their Low Voltage Distribution system in a different way. Three European network architectures are discussed briefly in Chapter three to highlight these differences. Much of America, Australia and the Pacific Rim distribute low voltage power in a very different fashion to Europe; networks tend to be overhead, small and provide electricity at 110 V. The characteristics of each of these networks differ, being more or less susceptible to noise ingress, experiencing higher or lower signal attenuation, exhibiting different levels of signal radiation and so on. To some extent, the same is also true for adjacent networks within national boundaries. As a result, Power Line Communication systems must be robust and flexible in order to be attractive to the widest possible market.

Chapter 3: Effects of the Distribution System on HF Signals

3.1 Introduction

The Low Voltage Distribution Network was designed to distribute ac power at low frequencies (50 to 60 Hz) with minimum attenuation. It was not designed to carry high frequency communications, and as such presents the designers of Power Line Communication systems with some unique problems.

A Low Voltage Distribution Network, including the industrial and domestic wiring on the end, is made up of electrical conductors of varying size, age and construction. Each network will have its own unique characteristics, so a PLC system must be adaptable in order to cater for most, if not all, eventualities. All electrical equipment connected to the ac power supply will generate some form of noise, which will be injected onto, and carried across, the Low Voltage Distribution Network. Household wiring can also be viewed as a large antenna, collecting any airborne HF signals and injecting them onto the distribution network. Chapter three describes in more detail the problems to be overcome when using the Low Voltage Distribution Network as a communications medium.

Transmission line theory can be used to model HF signal behaviour on a conductor, so long as the relevant parameters are known or can be determined. On a single-phase network the standard equations apply.

$$Z_0 = \sqrt{\frac{R + j\varpi L}{G + j\varpi C}}$$

$$\gamma = \sqrt{(R + j\varpi L)(G + j\varpi C)} = \alpha + j\beta$$

Z_0 = Characteristic Impedance

R = Resistance per unit length

L = Inductance per unit length

G = Conductance per unit length

C = Capacitance per unit length

γ = Propagation coefficient

α = Attenuation coefficient

β = Phase-change coefficient

A more complex variation of the standard equations are required for a three-phase low voltage distribution network, where the proximity of the conductors in relation to each other, along the length of the network, must be taken into consideration. A mathematical model for the test network in Kendal, using three-phase transmission line theory, was derived and forms part of a separate Ph.D. thesis [3.1].

3.2 Network architectures

3.2.1 Topology

Although there is commonality amongst low voltage distribution networks, there are regional and national differences in all. There is, therefore, no one model to exemplify a typical low voltage distribution network. The following examples will give some idea of the differences encountered.

3.2.1.1 UK model

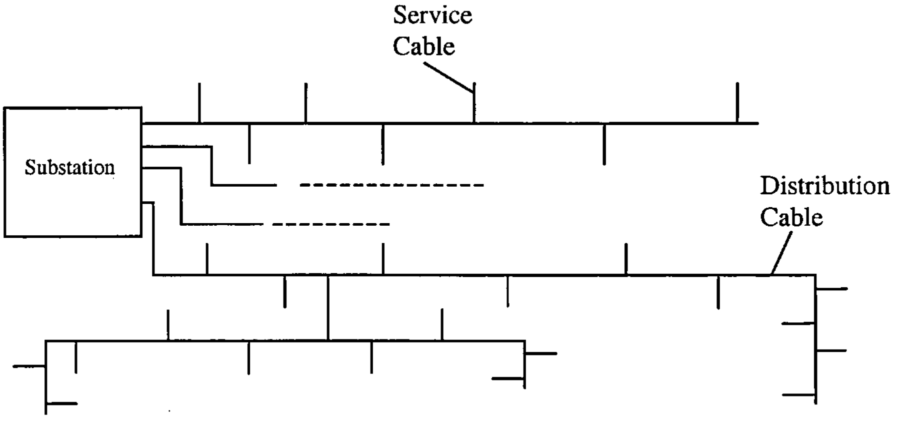


Figure 3.1: UK Low Voltage Distribution Network

In the UK a number of three-phase Distribution Cables run from the substation to the end of the network. Older cables may have a four-core construction with a metal sheath, one of the cores and the sheath providing a separate neutral and earth. In more recent times the old design has given way to a three-core construction with the metal sheath providing a combined neutral/earth. Depending on the size of network, and the demand, the cross-sectional area of the conductors may be reduced as the distances from the substation increases and the demand decreases. A distribution cable may branch one or more times along its length giving the whole network a tree and branch appearance. A typical distribution cable in the UK is approximately 250 m in length, although cable runs of twice this distance are not uncommon.

Close to where a customer is located, a Service Cable is spliced onto the distribution cable. In the UK, a single-phase service cable provides the customer with a 100 A, 230 V power supply. It is normal practice to rotate the service phase along the length of a distribution cable in order to share the load equally amongst all three phases. If a customer's power requirement exceeds the single-phase capability, three-phase service cables are available. Street lighting also obtains its power directly from the distribution cable.

Street pillars are not a common feature of UK low voltage distribution networks, therefore easy access to the cables is only available at the substation and at a customer's premises.

3.2.1.2 Swedish model

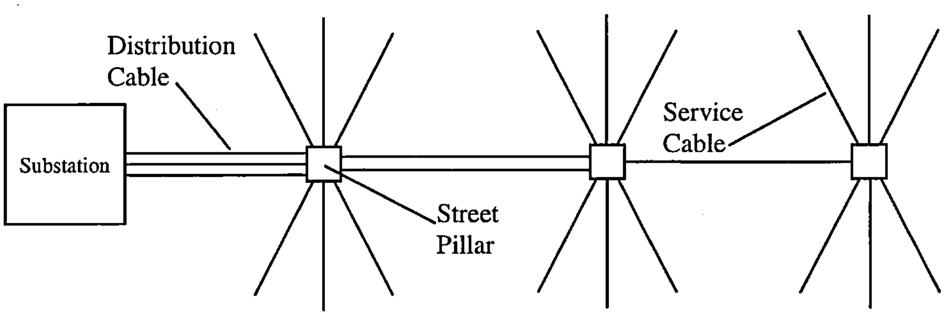


Figure 3.2: Swedish Low Voltage Distribution Network

In Sweden, distribution cables supply electricity to a number of street pillars positioned along the length of the network. Street pillars act as local distribution points to which customers are connected in a star configuration.

Distribution cable has a four-core construction with no metallic outer sheath. Three of the cores are phase conductors and the fourth provides a combined neutral/earth. Depending on network size, and the demand, two or three distribution cables run in parallel from the substation to a street pillar some distance away. Again, depending upon demand, a number of distribution cables run in parallel to the next street pillar and so on until the end of the network. As the distance from the substation increases, and the demand decreases, the number of distribution cables running in parallel is reduced. All customers are provided with a three-phase supply. The three-phase service cable is connected to the network at a street pillar.

Looped network sections are not uncommon in Sweden; this configuration allows load to be shared during periods of high demand. Due to the use of street pillars, easy access to the network is available at a number of points along its length. Street lighting is usually supplied from its own network, fed from the substation.

3.2.1.3 German model

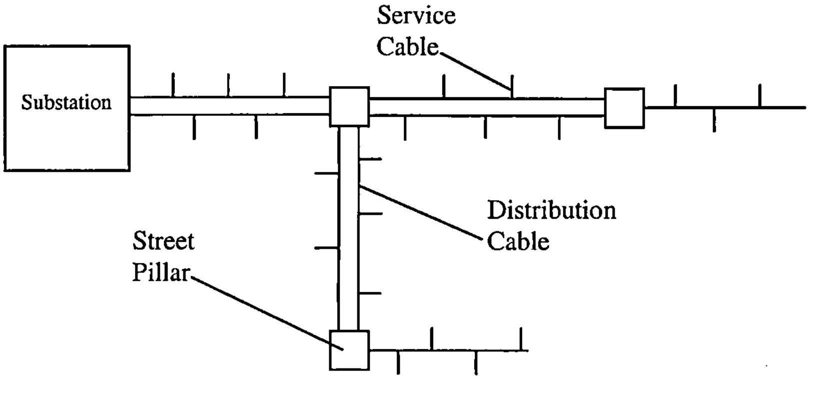


Figure 3.3: German Low Voltage Distribution Network

The German network topology shares similarities with both the UK and Swedish models. As in Sweden, distribution cables run in parallel from substation to street pillar and from street pillar to street pillar. Like the UK, customer services are obtained by splicing a service cable directly onto a distribution cable close to the point of demand.

Distribution cable has a four-core construction with no metallic outer sheath. Three of the cores are phase conductors and the forth provides a combined neutral/earth. Distribution cables run between street pillars where, if required, a network may branch off.

Looped networks are a common feature of the German network, allowing load to be shared during periods of high demand. All customers receive a three-phase supply. Due to the use of street pillars, easy access to the network is available at a number of points along its length. Street lighting is usually supplied from its own network, fed from the substation.

3.3 Power Line Noise

The characteristics of noise found on the mains network differ considerably, from high level impulsive noise generated by such things as thyristor phase control circuits, to relatively narrowband signals from television line time base circuits and induction cookers. With the increasing use of electronic devices, noise levels on unconditioned mains networks is likely to increase.

Much of the noise present on the mains will fall into one of the following categories.

3.3.1 Noise synchronous with the power frequency

This is noise caused by switching devices such as silicon-controlled rectifiers (SCRs). An SCR switches when the power voltage crosses a pre-set value. Since the voltage is cyclic, the SCR switches at the power frequency or multiples of the power frequency. Therefore, noise is generated at the power frequency or multiples thereof. This noise is synchronous with and drifts with the power frequency.

3.3.2 Noise with a smooth spectrum

This noise is generated by loads which do not operate synchronously with the power frequency, for example universal motors. Universal motors have brushes that cause current switching at intervals which depend on the speed of the motor. For most practical purposes this noise can be thought of as having a smooth spectrum without stationary spectral lines.

3.3.3 Single-event impulse noise

Lightning, thermostats and any single switching operation causes impulsive noise.

3.3.4 Nonsynchronouse periodic noise

This is noise which has a line spectra which is not synchronous with the power signal frequency, for example the television horizontal scanning line frequency and noise from induction cookers.

3.3.5 Signal interference

This includes all transmitted radio signals, within the frequency range of interest, picked up on a mains network being used for power line communication purposes. Signalling interference also includes mutual interference between mains-born signalling systems.

In the frequency range used by most of the power line communication systems, 3 kHz to 150 kHz, the main form of noise below 10 kHz comes from power signal harmonics. Above 10 kHz the noise which is most detrimental is generated primarily by appliances connected to the same transformer secondary to which the power line communication system is connected. Narrowband interference is generated by devices such as television line time-base circuits, switch-mode power supplies and induction heating and cooking equipment. Power frequency related disturbances from semi-conductor phase controls and random impulsive noise from commutator motors appear as broadband noise.

Two of the main sources of noise are triacs used in light dimmers and universal motors [3.2, 3.3].

3.3.6 Light Dimmers

In the domestic environment, solid state light dimmers can be used with up to 1000 watts of incandescent lighting. For industrial loads in excess of 3000 watts, light dimmers can be made to order but are not readily available 'off the shelf'. The dimmer is wired in series and controls lamp brightness by switching on and off rapidly through the use of triacs. The triacs generate noise which is synchronous with the power signal frequency and appears as harmonics of the power signal frequency.

Above 500 kHz, limits have been placed on the noise produced by light dimmers. However, in the frequency range used by most power line communication systems, no restrictions exist.

Even when lights are set to maximum brightness the triac still switches on and off, therefore noise is generated continuously during operation. Since the switching of the triac is much faster than the change in excitation voltage (power signal), high frequency components are produced.

$$\frac{dv}{dt} = \frac{100V}{\mu s} \qquad \textbf{(Eqn. 3.1)}$$

The triac switch closes early in the first half-cycle for maximum brightness and late in the first half-cycle for minimum brightness. During zero-crossing the triac switch opens. The process is repeated during the second half-cycle. The high-frequency voltage produced is a damped oscillatory waveform with natural resonant frequency of approximately 125 kHz.

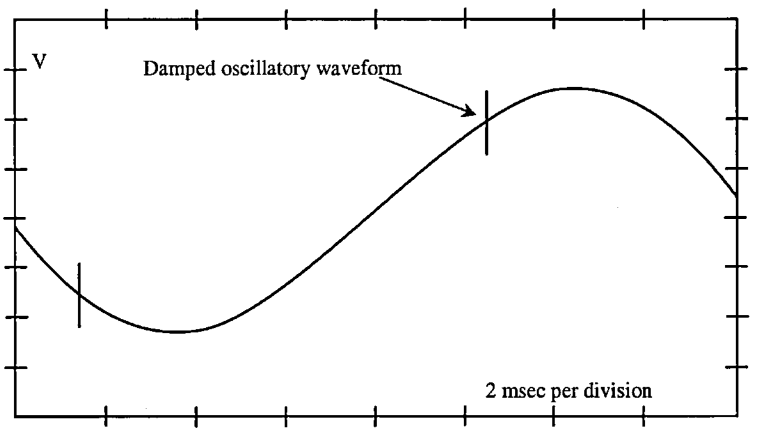


Figure 3.4: Voltage across the power circuit with a dimmer set for maximum brightness

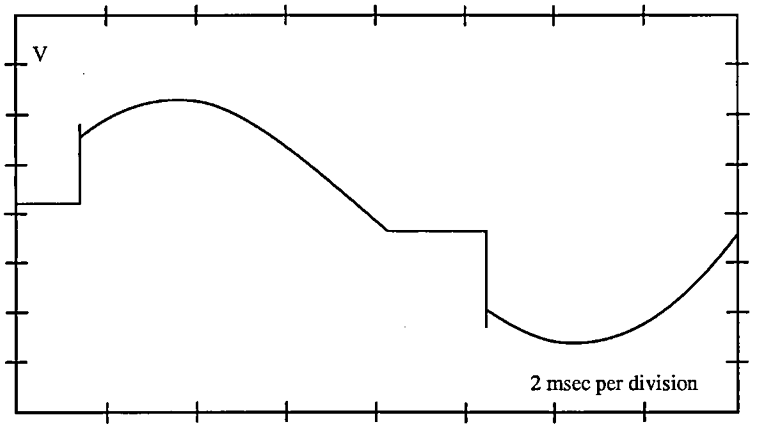


Figure 3.5: Current through 100 W lamp with dimmer set for maximum brightness

3.3.7 Universal Motors

Universal motors are small and lightweight and can be found in many everyday appliances such as: vacuum cleaners, mixers, blenders, sewing machines, portable hand-held sanders, drills and saws. They are series-wound motors, which can operate on a.c. or d.c. voltages. Their performance is similar to that of d.c. series motors. When a load is placed on the motor, the speed decreases; when the voltage to the motor is increased, the speed increases. Typical maximum speeds under full load range from 3,500 to 10,000 rpm. A series-connected, variable resistor can be used to obtain a continuously variable speed from the motor; changing the field winding can be used to obtain different discrete speeds. Some appliances also use solid-state switching devices to control their speed.

Universal motors generate noise because they use brushes, which cause a switching action. This noise is not generally synchronous with the power signal. The noise generated by motors with brushes has a random amplitude and frequency and can cause radio interference.

Figure 3.6 shows noise voltage spectra for a number of noise sources containing universal motors and triacs as well as background noise in a residential environment.

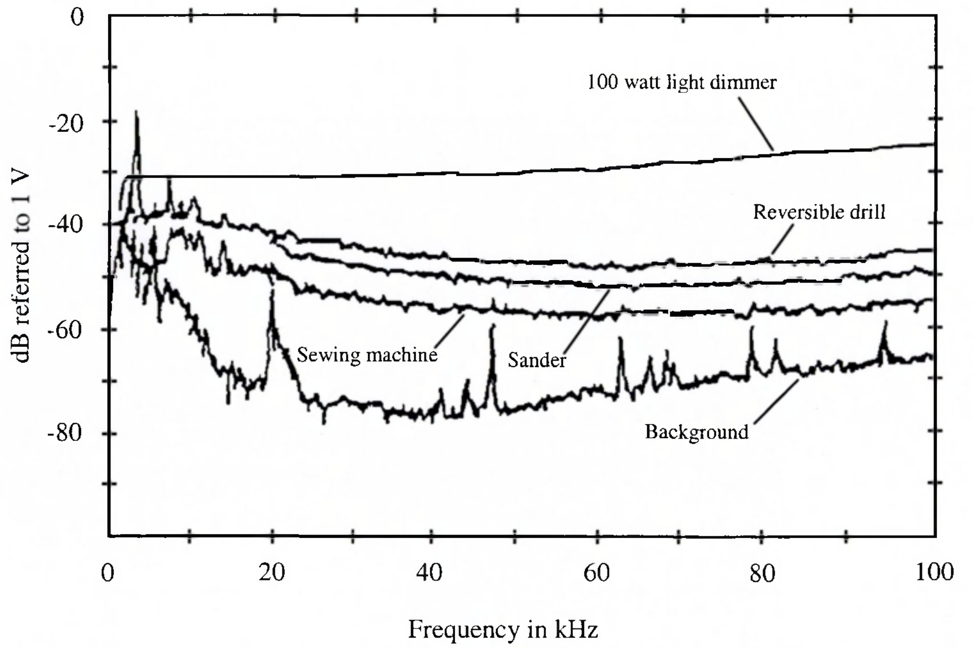


Figure 3.6: Voltage spectra for three universal motors and a light dimmer compared with typical residential background noise

In the frequency range from 150 kHz to 30 MHz electrical equipment for household, office and industrial use sold since 1977 is subject to legal requirements for the control of interference [3.4, 3.5]. The technical requirements are given in BS 800: 1983. All electrical equipment covered by the specification is required not to generate levels of r.f. voltage in excess of the limits specified. Equipment covered includes household and industrial appliances containing commutator motors, semi-conductor phase control circuits used for motor speed and lighting variation.

For a number of reasons some appliances do generate levels of disturbance which exceed those stated in BS 800: 1983:

1) Equipment sold before 1977, particularly in the long and medium wavebands.

2) Equipment where the suppression has been removed.

3) Industrial equipment used for spark erosion, argon arc welding, uninterruptible power supplies and solid state motor speed control.

4) Induction heating and cooking equipment.

5) Equipment producing discontinuous noise such as thermostats and relays used in central heating systems are subject to relaxed limits dependent upon the frequency of operation. The relaxation may be as high as 30 to 40 dB.

6) Transients generated by mains switching has no control.

Few forms of noise and interference are single frequency sources. In general they are harmonics of distorted waveforms, in many cases with low level amplitude and frequency modulation components present. The fundamental frequency of operation tends to be below the frequency range selected for most mains signalling equipment; for example the television line time frequency is approximately 15 kHz, switch mode power supplies and induction cookers operate in the range between 20 kHz and 40 kHz. However, harmonics from these sources may adversely affect power line communication signalling equipment.

Radio frequency voltage levels found on mains supplies in many industrial plants are well in excess of those found in the home. Frequencies in use may extend from a few hundred hertz up to about 1 MHz, depending on the application [3.4]. Table 3.1 shows the occurrence of transients and their amplitudes found in typical industrial and domestic premises.

Voltage Exceeding (volts)	50				100				200				400				600		
Duration Exceeding (microseconds)	0.1	1	10	100	0.1	1	10	100	0.1	1	10	100	0.1	1	10	100	0.1	1	10
E.R.A. sub-station	61	7.4	3	0.16	2.1	2.1	0.18	0.06	0.6	0.6	0.01		0.01	0.01					
L.E.B. sub-station	12.8	12.8	10	0.62	1.4	1.4	1.4	0.06	0.04	0.04	0.04		0.02	0.02					
Telephone Exchange (cable supply)	62	7.5	4.1	2.6	11.6	0.7	0.42	0.21	0.05	0.05	0.04		0	0					
Telephone Exchange (overhead line)									8.9	8.9	7.4	0.43	0.07	0.07	0.06	0	0.01	0.01	0
Domestic (cable supply)	240	174	65	0.5	13	13	2.4	0.19	0.38	0.35	0.10		0.02	0.02					
Domestic (overhead line)									394	394	94	1.1	15.2	15.2	2.5	0.01	0.06	0.06	0
E.R.A. Laboratory	216	65	2.9	0.22	5.7	2.1	0.17	0.04	0.37	0.13	0.01		0.03	0					
Industrial site	4470	3280	2630	1	1960	1890	1290	0.26	509	506	5.6		2	2					

Table 3.1: Average number of spikes per day exceeding certain voltage amplitudes and time durations [3.4]

Mutual interference between signalling systems may also be a problem. Tests indicate that the domestic meter will not attenuate signals on the mains in the frequency range of interest. It will therefore not act as a choke, isolating domestic power line communication signalling from utility power line communication signalling. This is undesirable and may be unacceptable. Two different signalling systems using the same transmission media may result in corrupted information for one if not both systems. A number of possible solutions do exist.

1) Domestic and utility power line communication systems could occupy different frequency bands.

2) Restricting transmission modes could segregate domestic and utility systems.

3) The inclusion of a filter at the electricity meter.

3.4 High frequency signals on distribution networks

In a normal communication or data network, the physical medium over which signals are transmitted, is designed for minimum signal attenuation. In order to achieve minimum attenuation, the characteristic impedance of each element of the network is fixed during manufacture. When all the elements are connected together to form a network, the overall characteristic impedance remains the same and transmitted high frequency signals are received with minimum attenuation.

The characteristics of low voltage distribution networks are optimised for the transmission of low frequency power signals (50 to 60 Hz) and not high frequency communication signals. Therefore, individual elements of the network are not manufactured to exhibit a uniform characteristic impedance at higher frequencies. At each discontinuity along an electricity distribution network, i.e. where one network element connects to another network element, an impedance mismatch will occur.

3.4.1 Discontinuities

The physical size, shape and position of a conductor help to determine its characteristic impedance. If there is a change in any one of the aforementioned elements the characteristic impedance also changes. A journey along part of one distribution cable will emphasise the size of the problem:

Starting at the bus-bars in a substation, the bus-bars have their own characteristic impedance. In a substation the distribution cable is stripped, and the individual conductors cut to length and shaped to connect to the bus-bars; this presents the second characteristic impedance. A third characteristic impedance can be seen where the conductors are brought together in the original distribution cable. A number of changes in characteristic impedance have been described inside the substation; the situation can only get worse outside.

At every point along the distribution cable where discontinuities occur there will be a change in impedance:

- Where one cable is jointed to another.
- Where a cable branches off from the main feeder.
- Where a service cable is spliced onto the distribution cable.
- Where cables are connected to street pillars.
- Where cable dimensions change.
- And numerous other points along the network.

There are, therefore, many opportunities for the impedance to change along the entire length of a low voltage distribution network, but what effect does this have on high frequency signals?

When a high frequency signal comes across a change in impedance, part of the original signal continues along the network and part is reflected. The following diagrams help to describe what happens to a single, high frequency signal along a very small section of network and highlights how complicated the situation soon becomes.

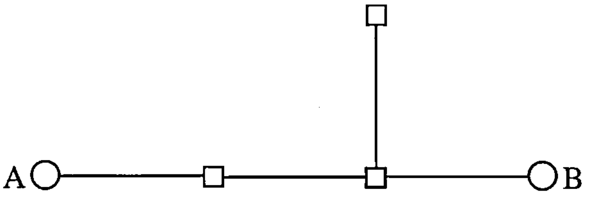


Figure 3.7: A sectional network element

Figure 3.7 represents a small section of distribution network with three discontinuities (represented by the three squares). A single frequency, HF signal is to be sent from A to B.

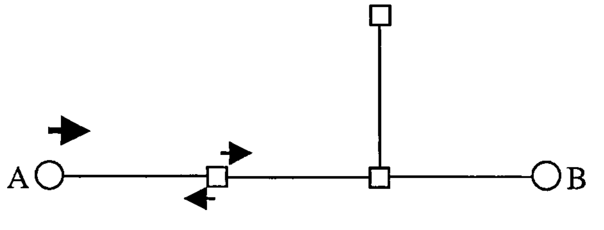


Figure 3.8: A sectional network element

When the signal meets the first discontinuity, part of the signal continues and part is reflected. Two things have now happened:

- The power of the original signal has been reduced, i.e. the signal is attenuated.
- The reflected signal has set up a standing wave on the cable. Standing waves lead to varying signal attenuation, which is position dependent. This is an important factor for power line communication systems where an end-user's location can be anywhere along the length of the network.

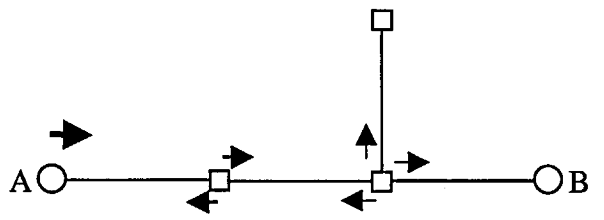


Figure 3.9: A sectional network element

At the second discontinuity the signal is again split and attenuated.

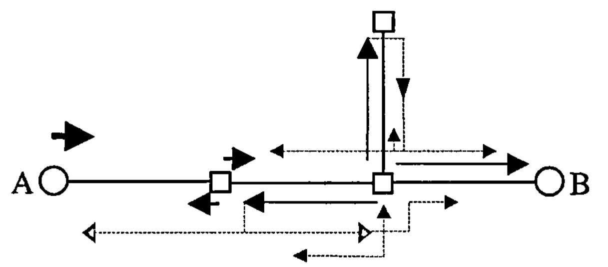


Figure 3.10: A sectional network element

Although the network and task is simple, figure 3.10 shows how complicated the pattern of attenuation and reflection soon becomes. Diagrammatically it would be difficult to go further without making the network schematic unintelligible. Figure 3.10 does, however, give some insight as to what is happening along the simple network section:

- The signal intended for (B) arrives at its destination with only a fraction of the power it started out with, i.e. the signal is attenuated.
- (B) receives the same signal a number of times although shifted in time and much reduced in power, due to reflections and reflections of reflections. This is known as multipath.
- A complicated pattern of standing waves has been set-up along the entire length of the network.

- Standing waves result in points of high attenuation across the network. The position of these points of high attenuation is frequency dependent. A worst case on a real network could mean a potential power line communication user may not be able to obtain a service if the system is narrow-band and a signal null occurs at the point where they wish to retrieve the signal.

The above demonstrates how complex signal behaviour is on a simple network using one frequency. The situation on a real distribution network using a band of frequencies will be much more complex. Any viable PLC solution must be capable of delivering a reliable service, despite the problems presented above.

3.4.2 Signal attenuation characteristics

If a signal is injected across a band of frequencies, onto the Low Voltage Electricity Distribution Network in a substation, and observed at the service termination point of each customer, a unique pattern of signal attenuation is seen at each location. If short-term noise transients are ignored, the attenuation characteristic remains constant over time, so long as the network itself does not change.

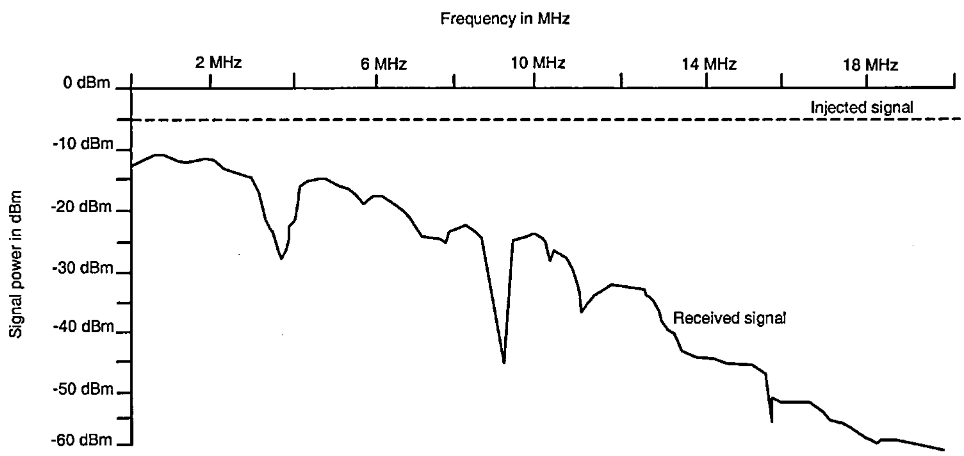


Figure 3.11: Attenuation characteristic at one point on a network

The attenuation characteristic at any point on a network is the result of a number of factors:

- Distance from substation.
- Position on the network.

As discussed in the previous section, the complex pattern of signal attenuation due to impedance mismatches, resulting in signal reflection and standing waves, produces a unique attenuation characteristic at each location on a network.

3.5 Network topology

Network topology determines the attenuation characteristics for the whole network. An electricity distribution network contains many elements: bus-bars; distribution cables of differing length, size, construction and age; service cables of differing length, size, construction and age; joints; street pillars, the list goes on and on. Each network element has some effect, large or small, on the signal attenuation characteristic at every point on the network. Under normal operating conditions, the topology of an electricity distribution network does not change and therefore the signal attenuation characteristic at every point along that network will not change.

From time to time, however, networks will change due to: fault conditions, operational requirements or network growth, to name but a few. It must be borne in mind that any change in a network's topology will result in a corresponding change in the signal attenuation characteristics of every point along that network. These changes may be insignificant and affect no one; on the other hand, the changes could result in the loss of service for some established PLC users. This is a rather over pessimistic view as, hopefully, a PLC technology should be flexible enough to overcome most network changes.

The first three chapters of this thesis have introduced the concept of Power Line Communications, placing the technology within an historic context, and discussed some of the issues, which must be addressed by any high frequency Power Line Technology in order to provide a viable service. Chapter four documents the research work carried out in Kendal, Cumbria, and discusses the rationale behind the techniques developed to analyse high frequency signals on the Low Voltage Distribution Network.

Chapter 4: Experimental work on the Kentrigg Network

4.1 Introduction

Research work started with an initial investigation into the pros and cons of remote meter reading and Utility control over customer supply and services. Remote meter reading offered automated data acquisition and billing, whilst the possibility of a larger number of charge bands throughout a twenty-four hour period promised a much more realistic pricing structure for electricity [4.1]. At the same time, Electricity Utilities would be provided with the ability to remotely control customer loads.

Electricity is generated in order to supply customer demand as it fluctuates throughout the day. To guarantee this supply, much time and effort is spent predicting probable demand throughout the day. These predictions are based on a multitude of inputs including:

- Long-term trends (what happened on the same day in previous years).
- Recent trends
- Weather
- Season
- National and regional events, and the time these events take place. (Everyone making a cup of tea during the break in a national sporting event has to be predicted and a suitable increase in supply provided at the right time).

The electricity generating hierarchy is made up of generating plant that has a long start-up or shutdown cycle, and plant that can be brought on-line at relatively short notice. Nuclear and solid fuel power stations are examples of the former, whilst gas and oil fired power stations are examples of the latter. Long-cycle power stations will generate electricity most of the time but cannot react quickly enough to account for short-term fluctuations. The cost of the plant can be spread over the lifetime of the power station and so the cost of generating electricity is relatively cheap. Short cycle generating plant is required for daily fluctuations that cannot be supported by the larger, permanently on, stations. These power stations are not continuously generating electricity, the cost of the plant can only be recouped during the generating cycle and therefore the relative cost of electricity generated in one of these power stations is much higher. By increasing the number of charge bands a more realistic, graded pricing structure could be introduced, offering cheaper electricity at night or during the quieter parts of the day and more expensive charges during peak periods. Potential savings in electricity bills would encourage customers to modify their electricity usage and reduce demand for expensive electricity during peak periods. The daily load curve could be further managed by allowing the Electricity Utility to control certain, non-critical, industrial and domestic loads.

Although the benefits from power line technology to the electricity supply industry seemed attractive on the surface, it was obvious to the research group that the cost of deploying such a system into every home, office and factory in the country was prohibitive. The cost of introducing any new technology would have to be shared by the Utilities and their customers. Although large electricity users could benefit from an increased number of charge bands; and therefore may be prepared to shoulder some of the implementation cost, smaller users, including the domestic market, would not. Additional, value added, services must also be offered in order to generate the required market interest.

The proposed increase in services suggested a way forwards commercially, but introduced a couple of new technical problems.

1. With an increase in the number of in-house services on offer, and with little attenuation between adjacent properties, interference from other power line users would inevitably cause problems.

2. The existing CENELEC bands for power line communications, 3 kHz to 148.5 kHz offered a very narrow bandwidth with slow data rates.

A possible solution to issue (1) was developed during the early stages of the research. In order to reduce interference between adjacent users some form of isolation was required between the in-house and access networks. A Conditioning Unit was developed which provided isolation between the two networks and offered a convenient location for signal injection and retrieval.

The bandwidth offered by the CENELEC bands could not support the high-speed data required by value-added services such as Internet access, security systems or interactive television. Much greater bandwidth and higher frequencies would have to be used if effective services were to be developed. This research was therefore based around the use of frequencies above 1 MHz.

4.2 Network Conditioning

4.2.1 Design Rules

The need for some form of mains filtering, or network conditioning, at each customer/REC interface was realised at an early stage in the research. The reasons were as follows:

1) Household wiring acts as an aerial, picking up high frequency signals, which are passed onto the low voltage electricity distribution network.

2) There are a growing number of domestic mains-born signalling products available in the high street, i.e. baby alarms, computer modems etc.. The signals generated by these products pass onto the low voltage distribution network and could interfere with communication signals. In addition, with relatively low attenuation between adjacent domestic residences, unwelcome interference between neighbouring properties using similar systems would become a problem. As with (1) above, some form of filtering preventing high frequency signals passing from the house onto the low voltage distribution network is required.

3) High frequency transient noise present on the low voltage distribution network is passed onto domestic wiring.

4) It is also necessary to block any high frequency communication signals entering household wiring, in order to stop interference with domestic equipment, and to prevent radiated signal interference. As with (3) above, some form of filtering preventing high frequency signals passing from the low voltage distribution network is required.

In addition to the above, a unit placed at the customer/REC interface offers a convenient signal injection/retrieval point. The customer/REC interface is the point at which the service cable provided by the supplier is terminated and the customers wiring begins. In a typical UK domestic residence a single phase service cable is terminated in a service cut-out which contains the REC's 100 A HRC fuse, the customer's domestic supply is taken from this point via the electricity meter.

The concept of introducing a filter element in order to help facilitate power line communications is not a new one, however, largely due to the low frequencies used in traditional power line communication systems the price and complexity of such devices have been prohibitive. One suggested solution involves the use of a notch filter [4.2], reducing the available bandwidth to a single spot frequency. The filter is not placed in series with the electricity supply but is wrapped round the service cable close to the service cut-out in a similar way to a current transformer. In addition the unit requires its own power supply.

Any filter element designed for use with communication signals superimposed on the electricity supply must not affect the 50 Hz power signal. If the frequency of the communication signal is not far removed from the power signal, as is the case with systems using the frequency range 3 kHz to 145.8 kHz, the filter characteristics required increase the complexity of the circuit design. The price, complexity and limited usefulness of such filters preclude them from the mass market required for a successful power line communication system.

Economic viability has to be the overriding concern if any product is to be successful in the market place. Therefore any system or component part of that system, such as a conditioning element, will have to be cheap to manufacture and install, especially if one is required at every customer/REC interface. The practical limitation for most power line systems is the traditional frequency range used. These low frequencies not only offer slow and limited data throughput but require complicated and expensive solutions.

If a broad band of much higher frequencies were to be used, the problems mentioned above for traditional systems do not apply. Instead of complicated notch or band-pass filters a simple series low-pass design can be used. The design must be capable of attenuating high frequency signals, whilst at the same time safely carrying the full domestic power supply, including fault currents. The design must not attenuate the 50 Hz power signal and when measured at rated current the voltage-drop across the filter should not exceed 1 V r.m.s. as stated in CENELEC standard EN 50065. Such a design made up of capacitive and inductive elements could be produced cheaply and yet provide the attenuation required, if the signalling frequencies used are in excess of 1 MHz.

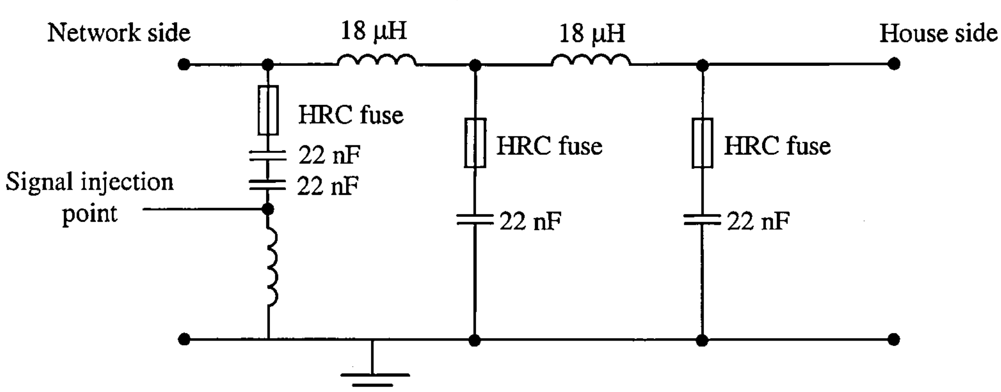


Figure 4.1: Conditioning Unit design

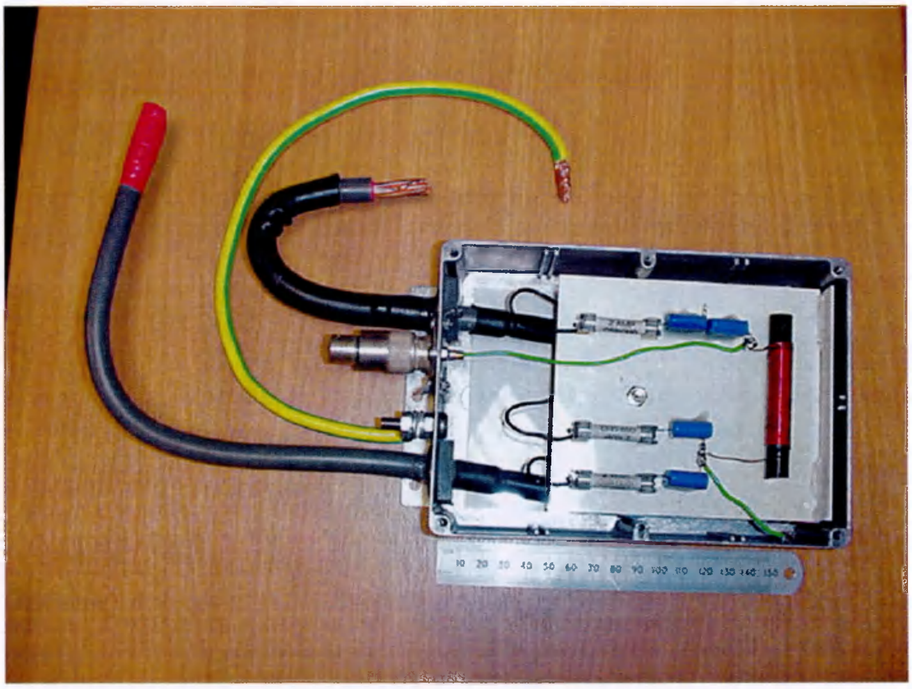


Figure 4.2: Conditioning Unit showing injection circuitry, shunt capacitors and HRC fuses

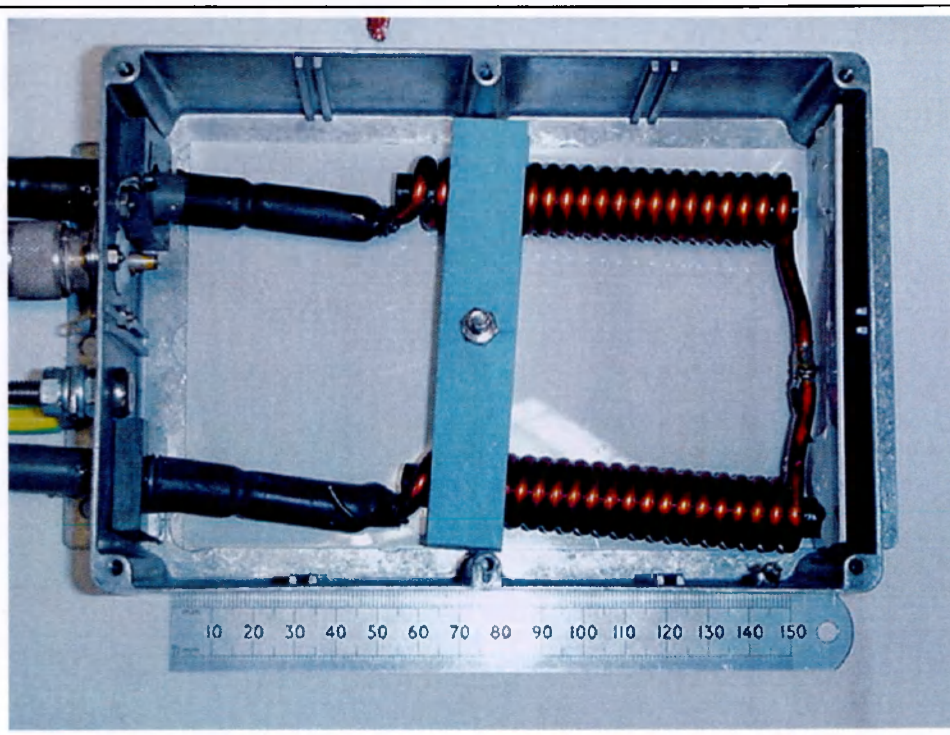


Figure 4.3: Conditioning Unit showing series inductors

4.2.2 Choke design and construction

Although the filter design was simplified by using a broadband design, the construction of the inductive element was complicated by the fact that it had to carry the full domestic load and be capable of withstanding any fault current. Solid copper conductor of 12.5 mm² was chosen and wound round a 78.5 mm² ferrite core. In order to obtain even small values of inductance, individual inductor sections must be physically large. For example, to obtain an inductance of 18 μH, the inductor measures approximately 85 mm in length and has a 17 mm diameter. In order to ensure safety, the inductive assembly (live conductor) within the conditioning element must be manufactured out of one length of copper bar, thereby increasing the complexity of manufacture.

4.2.3 Design criteria for the filter section

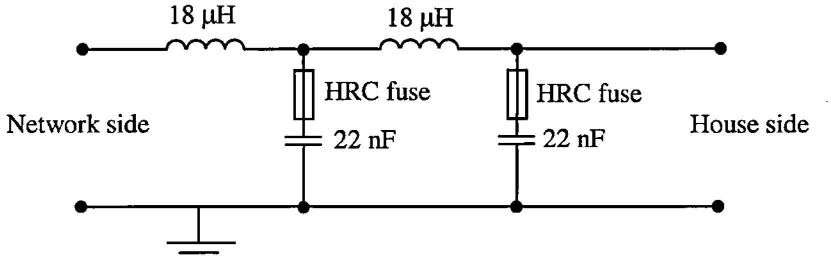


Figure 4.4: Filter design for the Conditioning Unit

The network side of the conditioning element is the point at which communication/data signals are injected and retrieved. Therefore looking into the house from the network, a capacitive shunt for the purpose of eliminating unwanted high frequency signals is not possible at this point. Instead a 'choking' impedance must be presented to frequencies above 1 MHz, preventing high frequency signals entering the house but not shunting any communication signals to earth. The wound inductors provide the necessary inductance but as previously stated the physical size restricts the achievable value. 18 μH per inductor is a representative value.

On the house side of the conditioning element, a shunt capacitor provides a path to earth for high frequency noise present on household wiring, whilst the inductor blocks high frequencies from entering the low voltage distribution network.

Transients with amplitudes of 2 to 4 kV but of short duration, 0.1 to 60 μs, are not uncommon on the distribution network. Any capacitor connected across the mains supply will be exposed to these transients, which could lead to dielectric break-down with low insulation between live and earth as a result. Capacitors used for suppression purposes between 230 V and earth must fall within two categories, X and Y in order to comply with BS EN 132400 'Fixed capacitors for electromagnetic interference suppression and connection to the supply mains'. Class X capacitors are for use in positions where a capacitor failure would not expose anybody to danger of electric shock and Class Y capacitors are for positions where a capacitor failure could expose somebody to dangerous electric shock. There is a limited range of values available for this type of suppression capacitor, usually in the range 1 to 22 nF. 22 nF Class Y capacitors were chosen for the conditioning element.

4.2.4 Design criteria for the coupling section

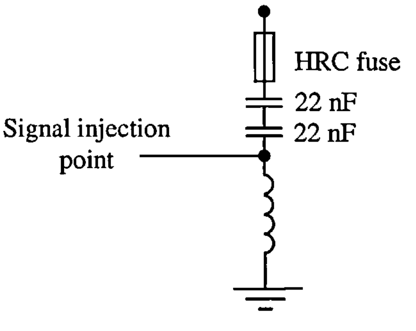


Figure 4.5: Coupling design for the Conditioning Unit

The coupling section had to provide a safe access point onto the low voltage distribution network for communication/data signals. In addition to the safety aspect there was a requirement for access to a broad band of frequencies from 1 to 30 MHz. A tuned circuit was obviously not good enough and a variable tuned circuit would only add complexity and hence cost. Capacitive coupling offered both simplicity and a broad bandwidth. Safety was increased by the inclusion of two coupling capacitors in series and a HRC fuse. A small inductor provided a path to earth for any fault current.

Traditionally, filters, attenuation networks and couplers are designed to match the characteristic impedance of the system into which they are placed. Realistically this is not possible for power line systems. As stated in Chapter 3, the characteristic impedance of the low voltage distribution network and in-house wiring is not fixed but dynamic, and alters as a result of network architecture, usage, measuring position on the network and time of day. The cost of producing and installing an active equalisation unit at every customer/REC interface would be prohibitive when the overriding concern is to provide an affordable service.

The conditioning element is a compromise between what is desired and what is realistically achievable on a network whose characteristic impedance may vary from something less than 10 Ω to something greater than 75 Ω.

4.3 Applerigg

In order to obtain meaningful results, access to the Low Voltage Electricity Distribution Network was essential. NORWEB plc (later to become a part of the United Utilities group of companies) gave its permission for a section of network to be made available. Kentrigg substation supplied a residential area in Kendal, Cumbria. The substation was located on Burneside road, at the entrance to Applerigg, a small residential cul-de-sac, and contained enough spare ground for a small research cabin to be erected within the compound. The 11 kV/400 V transformer supplied four spurs: Applerigg, Burneside road North, Burneside road South and Kentrigg, each spur being between 250 m and 350 m in length.

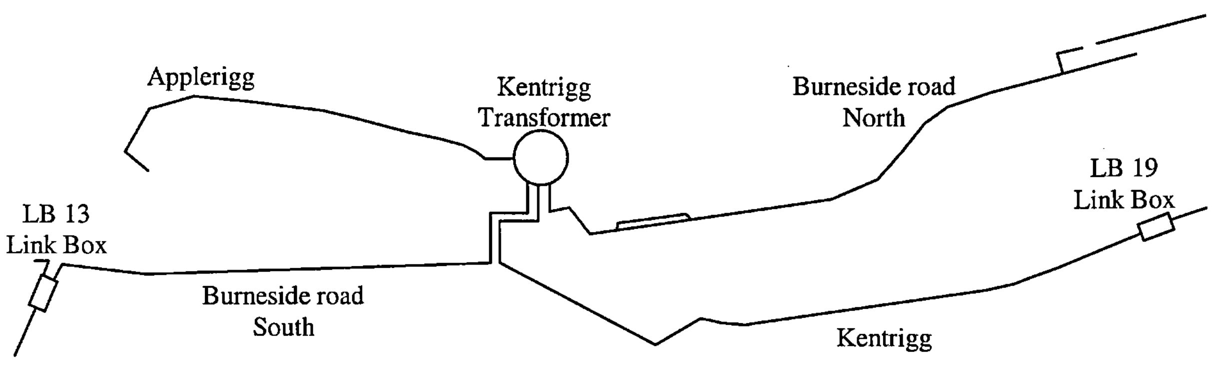


Figure 4.6: Three Phase Low Voltage distribution schematic of the Kentrigg substation

The Applerigg cul-de-sac contained 25 single-phase domestic customers; one of these customers was the research group's Industrial leader Dr Paul Brown, who conveniently lived towards the far end of the Applerigg spur at number 30. Applerigg provided access to the electricity network at two convenient locations: at the network hub, i.e. the substation, and at a point approximately 270 m away at Dr Brown's house. Figure 4.7 shows the layout of the properties fed by the Applerigg spur.

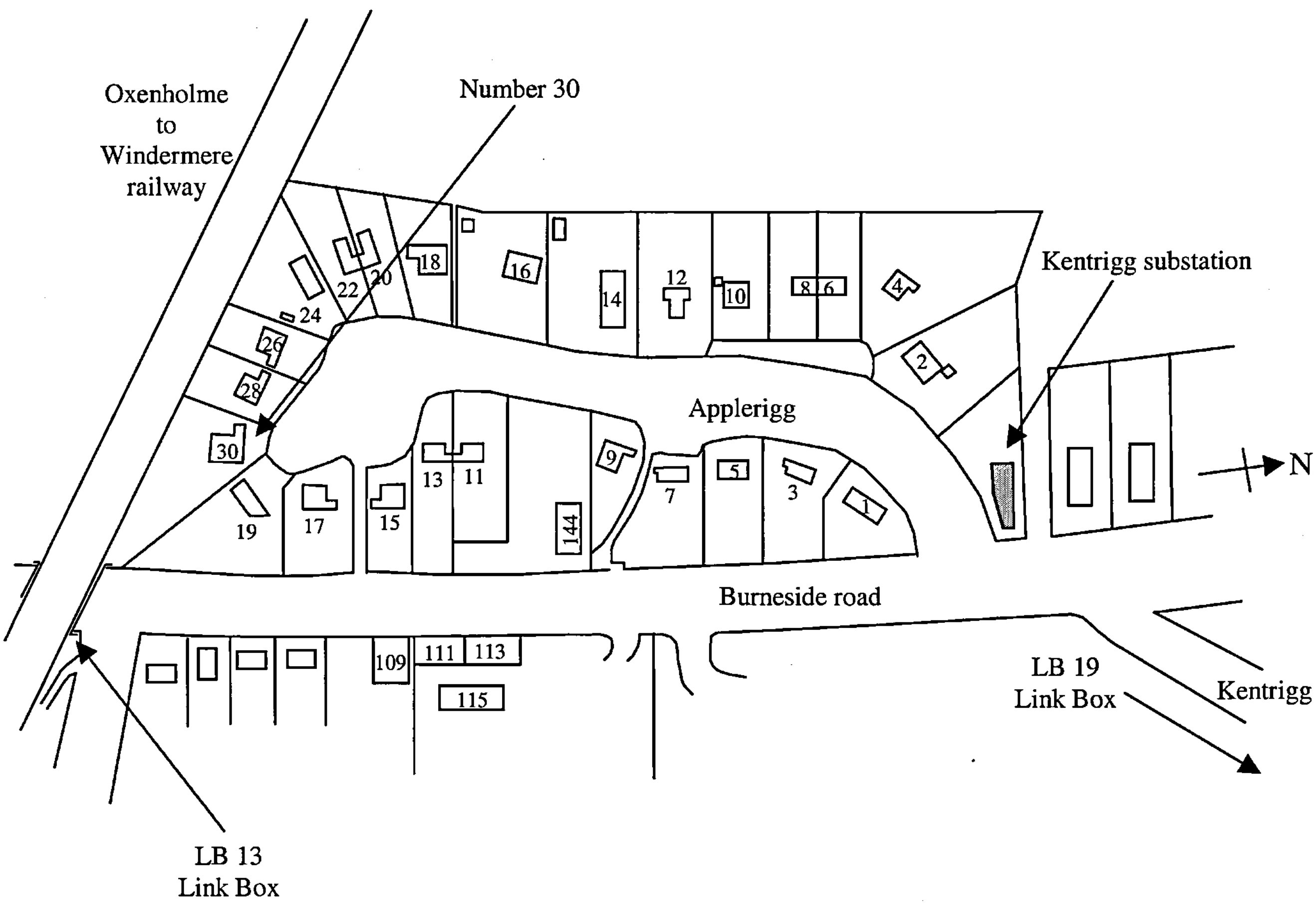


Figure 4.7: Applerigg showing the position of the substation and number 30

Just outside the substation compound a connection was made to each of the three phases of the Applerigg spur and brought back into the cabin. Figure 4.8 shows a more detailed plan of the Kentrigg compound.

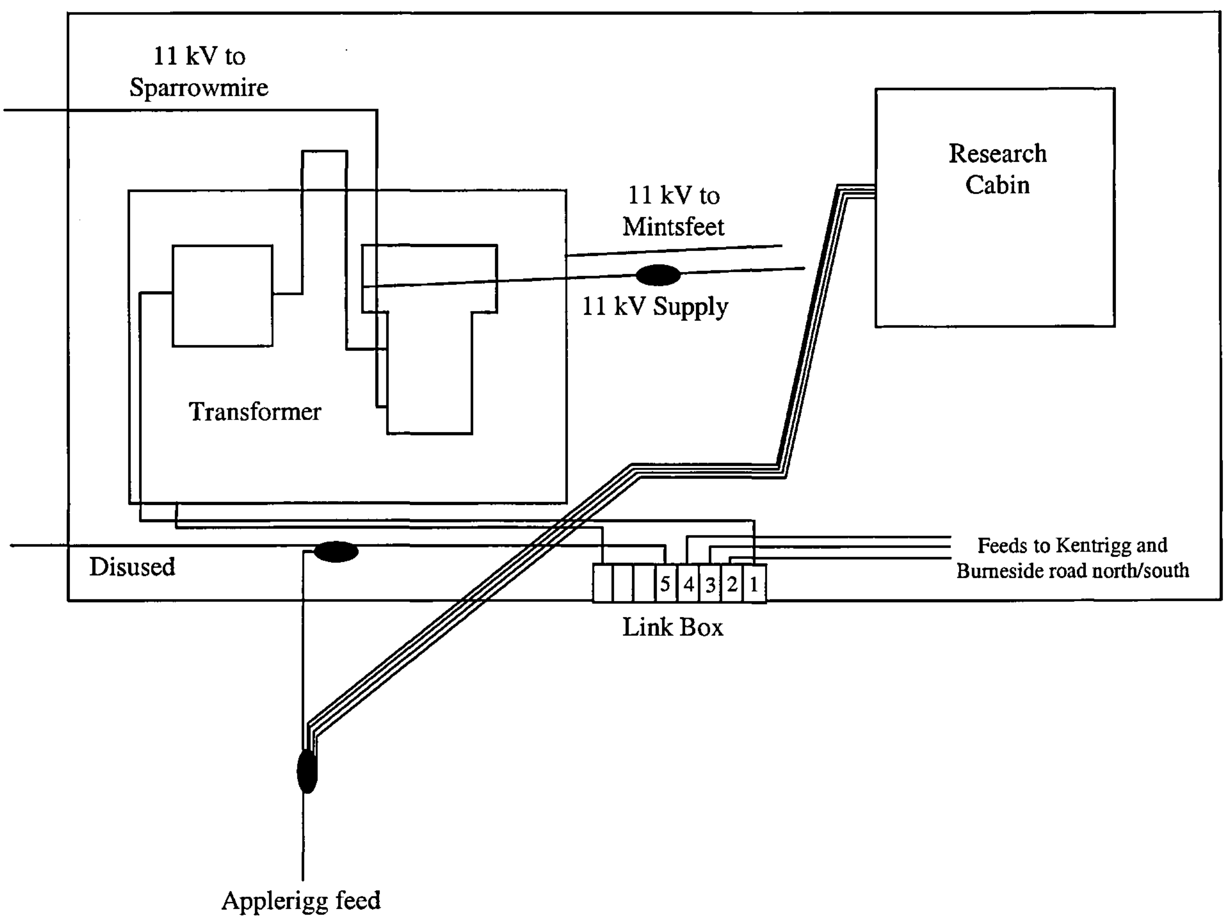
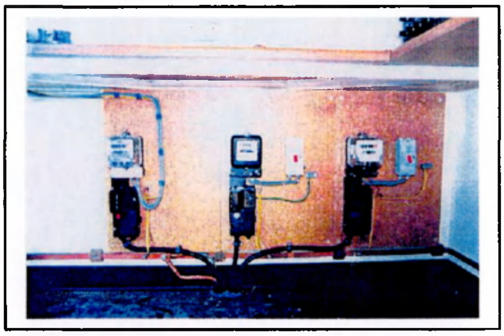


Figure 4.8: Kentrigg substation compound



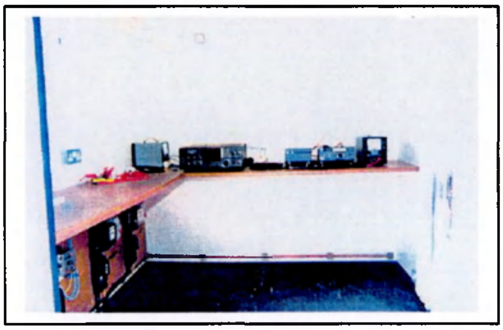


Figure 4.9: Inside the research hut in the Kentrigg compound

Inside the research cabin each phase was terminated in a service termination block to which a high frequency coupling devise was connected. Conditioning Units were not required in the cabin because no current was to be drawn from the single-phase supplies.

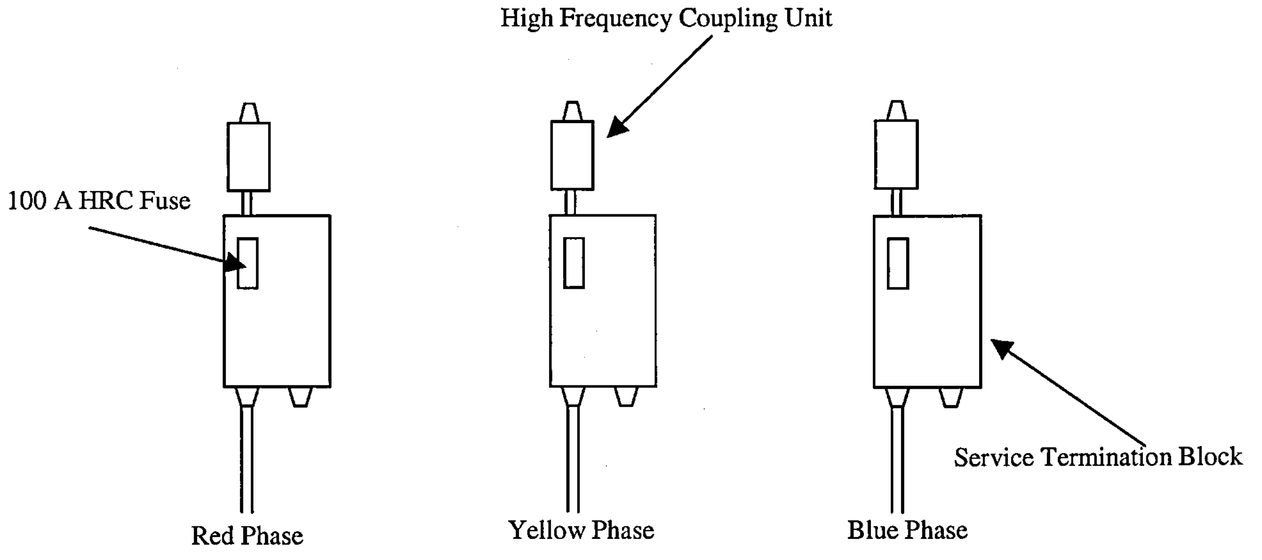


Figure 4.10: Service terminations inside the research cabin

Access at the far end of the Applerigg spur was gained inside the garage of number 30. A Conditioning Unit was installed between the service termination block and the electricity meter as detailed in figure 4.11.

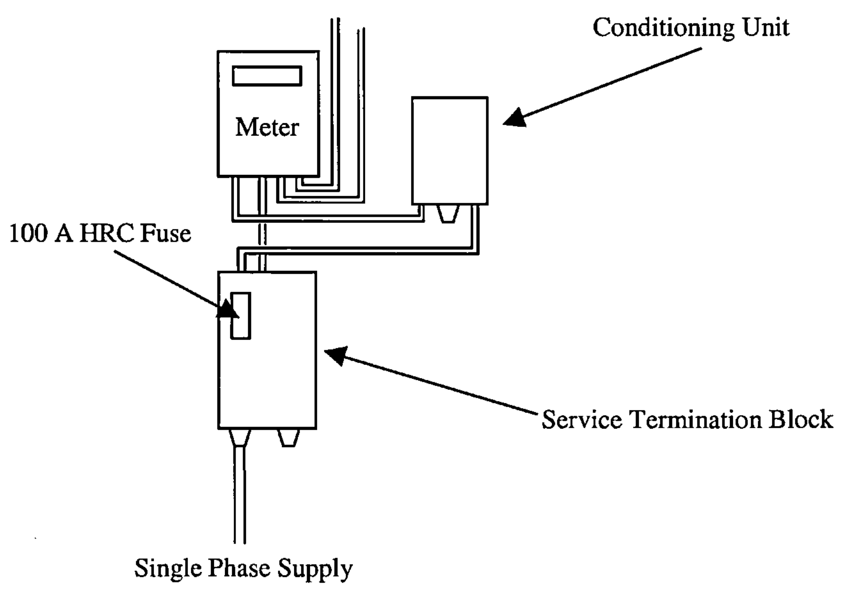


Figure 4.11: Position of the Conditioning Unit at number 30 Applerigg

4.4 Test Equipment

Although access to the Low Voltage Electricity Distribution Network had been provided in Kendal, the research group did not have access to the sort of specialised test equipment usually associated with high frequency research. The work was to be carried out away from university facilities and over an extended period of time. The cost of purchasing or hiring signal generators and spectrum analysers for use on just one project was prohibitive and could not be justified. As a result there was a need to develop novel testing techniques, using readily available equipment at a reasonable cost.

Dr Brown possessed an amateur radio licence, which facilitated the purchase of two, 100 W, HF radio transceivers. Both transceivers operated in the frequency range 1.6 MHz to 30 MHz, they had a variable transmit power level and contained a received power meter (S-meter). The transceivers operated in three modes: Single Sideband (SSB), Amplitude Modulation (AM) and Frequency Modulation (FM). A portable Roberts radio with its own S-meter also provided a lightweight mobile testing facility. All of this equipment was calibrated at regular intervals against more typical laboratory test equipment. Table 4.1 shows a calibration record for the Roberts radio.

Roberts Radio serial No. 7923807 Calibration data with added 6 dB attenuation pad								
Frequency (MHz)	Signal Level (dBm)	S Meter	Frequency (MHz)	Signal Level (dBm)	S Meter	Frequency (MHz)	Signal Level (dBm)	S Meter
1.5	-79.6	S1	4.5	-94.8	S1	7.5	-94.9	S1
	-74.3	S2		-89.3	S2		-90.0	S2
	-70.2	S3		-85.6	S3		-85.5	S3
	-67.5	S4		-82.8	S4		-82.6	S4
	-45.9	S5		-62.0	S5		-61.5	S5
	-35.2	S6		-50.8	S6		-50.2	S6
	-30.3	S7		-45.3	S7		-45.1	S7
2	-89.6	S1	5	-95.2	S1	8	-95.7	S1
	-83.5	S2		-89.7	S2		-89.1	S2
	-79.5	S3		-85.7	S3		-86.0	S3
	-79.7	S4		-82.6	S4		-83.5	S4
	-55.5	S5		-61.3	S5		-62.6	S5
	-44.6	S6		-51.0	S6		-51.0	S6
	-39.4	S7		-45.3	S7		-46.1	S7
2.5	-96.9	S1	5.5	-95.7	S1	8.5	-96.6	S1
	-90.2	S2		-89.3	S2		-90.2	S2
	-86.4	S3		-84.6	S3		-86.1	S3
	-83.4	S4		-82.1	S4		-83.0	S4
	-61.9	S5		-61.4	S5		-62.9	S5
	-51.2	S6		-50.2	S6		-51.3	S6
	-46.2	S7		-45.0	S7		-46.3	S7
3	-98.2	S1	6	-94.7	S1	9	-95.9	S1
	-92.9	S2		-89.3	S2		-90.7	S2
	-88.6	S3		-84.9	S3		-86.9	S3
	-86.0	S4		-82.2	S4		-84.0	S4
	-64.9	S5		-61.3	S5		-63.1	S5
	-53.2	S6		-50.2	S6		-52.1	S6
	-48.6	S7		-45.3	S7		-46.4	S7
3.5	-96.7	S1	6.5	-95.6	S1	9.5	-96.8	S1
	-91.4	S2		-89.4	S2		-90.5	S2
	-87.4	S3		-84.9	S3		-87.0	S3
	-84.1	S4		-81.8	S4		-84.1	S4
	-63.7	S5		-60.9	S5		-63.4	S5
	-53.0	S6		-50.0	S6		-52.3	S6
	-47.5	S7		-45.1	S7		-46.4	S7
4	-96.6	S1	7	-95.4	S1	10	-96.5	S1
	-90.4	S2		-89.6	S2		-91.1	S2
	-86.6	S3		-85.0	S3		-87.1	S3
	-83.5	S4		-81.8	S4		-84.0	S4
	-62.7	S5		-61.4	S5		-63.4	S5
	-51.1	S6		-50.8	S6		-52.2	S6
	-46.0	S7		-45.5	S7		-47.1	S7

Table 4.1: Typical calibration record for the test equipment

Testing could not be automated and each result had to be written down or typed into a computer before being plotted in Microsoft Excel. The majority of the results were recorded every 500 kHz over the frequency range 1.6 MHz to 10 MHz; this was a compromise between the level of detail required (the resolution) and the amount of time needed to complete each frequency sweep. Initially, results were observed every 100 kHz, which required 85 separate entries. With plans to test all three phases at multiple sites around Applerigg, and for those tests to be repeated regularly at different times of the day and night, recording results every 100 kHz, proved too slow a technique. Taking readings every 500 kHz reduced the number of entries to 18, which resulted in more blocky graphs, but the overall trend could still be observed. 100 kHz spacing was still used when more detailed plots were required.

4.5 Test Results

4.5.1 Noise

In order to determine the minimum level of power required to guarantee that a signal could be received at the furthest points on the Kentrigg network, it was necessary to determine the level of background noise found on the network. Results in the research hut were obtained by connecting a transceiver to each of the phases in turn and recording the position of the S-meter at frequency intervals of 100 kHz initially, and then 500 kHz, in the frequency range 1.6 MHz to 10 MHz. The S-meter readings were then converted to dBm using conversion tables similar to the one described for the Roberts radio, before being fed into a Microsoft Excel spreadsheet and a graph plotted. The same process was followed in the garage at number 30 Applerigg where one phase was available for testing. The following table and graph show a typical set of results obtained in the research hut.

Freq. (MHz)	Blue Noise		Yellow Noise		Red Noise	
	S-Meter	dBm	S-Meter	dBm	S-Meter	dBm
1.6	5.5	-96	7.8	-82.2	8	-81
1.7	8.2	-80	9.2	-73.8	9	-75
1.8	8.5	-78	9.4	-72.6	5	-70
1.9	8.2	-80	9.2	-73.8	5	-70
2	7.8	-82	8.5	-78	5	-99
2.1	7.8	-82	8	-81	6.2	-92
2.2	7.8	-82	8	-81	5.5	-96
2.3	8.2	-80	7.5	-84	5.8	-94
2.4	8.5	-78	6.8	-88.2	5.5	-96
2.5	8.5	-78	7.2	-85.8	5	-99
2.6	8.7	-77	7.5	-84	5.8	-94
2.7	9	-75	8	-81	7	-87
2.8	9.2	-74	8.5	-78	6.2	-92
2.9	9.4	-73	9	-75	4.5	-102
3	9.4	-73	9	-75	6.2	-92
3.1	8.5	-78	8.5	-78	5.5	-96
3.2	6.8	-88	8.5	-78	6.2	-92
3.3	7.8	-82	8.2	-79.8	5	-99
3.4	7.8	-82	7.8	-82.2	5.2	-98
3.5	7.5	-84	7.2	-85.8	4	-105
3.6	7.2	-86	5.8	-94.2	4.5	-102
3.7	6.5	-90	5.5	-96	4.5	-102
3.8	4.5	-102	6.5	-90	4.5	-102
3.9	2.2	-116	6.8	-88.2	3.8	-106
4	4.5	-102	7.2	-85.8	5.5	-96
4.1	5.5	-96	7.5	-84	2.2	-116
4.2	6.5	-90	7.5	-84	2.2	-116
4.3	7	-87	7.5	-84	6	-93
4.4	7	-87	7.2	-85.8	2	-117
4.5	6.8	-88	6.5	-90	2.5	-114
4.6	6.2	-92	6.2	-91.8	2.5	-114
4.7	6	-93	5.2	-97.8	2	-117
4.8	5.5	-96	5	-99	2	-117
4.9	5	-99	4.5	-102	1.8	-118
5	4.8	-100	5	-99	2	-117
5.1	4.8	-100	5	-99	1.8	-118
5.2	4.8	-100	5.2	-97.8	1.5	-120
5.3	5	-99	5.2	-97.8	1	-123
5.4	5.2	-98	5.5	-96	2.5	-114
5.5	5.5	-96	5.5	-96	2	-117
5.6	5.8	-94	4.2	-103.8	2	-117
5.7	6	-93	1.8	-118.2	2	-117
5.8	6.2	-92	1.5	-120	1.5	-120
5.9	6.2	-92	205	-114	1	-123

Freq. (MHz)	Blue Noise		Yellow Noise		Red Noise	
	S-Meter	dBm	S-Meter	dBm	S-Meter	dBm
6	6.2	-92	205	-114	3.5	-108
6.1	5.5	-96	102	-121.8	1	-123
6.2	4.5	-102	0.8	-124.2	0.5	-126
6.3	4.8	-100	0.8	-124.2	0.5	-126
6.4	2.8	-112	0.8	-124.2	1	-123
6.5	1.8	-118	0.8	-124.2	0.5	-126
6.6	0.8	-124	1.2	-121.8	0.5	-126
6.7	4	-105	2.5	-114	0.5	-126
6.8	4.5	-102	4.2	-103.8	0.5	-126
6.9	5.2	-98	4.2	-103.8	0.5	-126
7	5.5	-96	4.5	-102	0.5	-126
7.1	5.8	-94	2.8	-112.2	0.5	-126
7.2	5.8	-94	2.5	-114	0.5	-126
7.3	5.5	-96	2.5	-114	0.5	-126
7.4	5.2	-98	2	-117	1	-123
7.5	4.8	-100	2	-117	0.5	-126
7.6	4.5	-102	2	-117	2	-117
7.7	4.8	-100	2	-117	1	-123
7.8	4.2	-104	2.2	-115.8	0.5	-126
7.9	2.5	-114	2.2	-115.8	0.5	-126
8	2.2	-116	2.8	-112.2	3	-111
8.1	1.5	-120	4.8	-100.2	2	-117
8.2	0.8	-124	1.8	-118.2	2	-117
8.3	0.8	-124	0.8	-124.2	2	-117
8.4	0.8	-124	0.8	-124.2	2	-117
8.5	0.8	-124	0.8	-124.2	2	-117
8.6	0.8	-124	0.8	-124.2	3	-111
8.7	0.8	-124	0.8	-124.2	2	-117
8.8	0.8	-124	0.8	-124.2	2	-117
8.9	0.8	-124	0.8	-124.2	0.5	-126
9	0.8	-124	0.8	-124.2	1	-123
9.1	0.8	-124	0.8	-124.2	1	-123
9.2	0.8	-124	0.8	-124.2	3	-111
9.3	0.8	-124	0.8	-124.2	0.5	-126
9.4	0.8	-124	1	-123	2.5	-114
9.5	0.8	-124	1	-123	0.5	-126
9.6	0.8	-124	1	-123	0.5	-126
9.7	0.8	-124	2	-117	3	-111
9.8	0.8	-124	2	-117	1.5	-120
9.9	0.8	-124	2	-117	2.5	-114
10	0.8	-124	2	-117	0.5	-126

Table 4.2: Background Noise results for all three phases in the research hut taken on 26/08/92

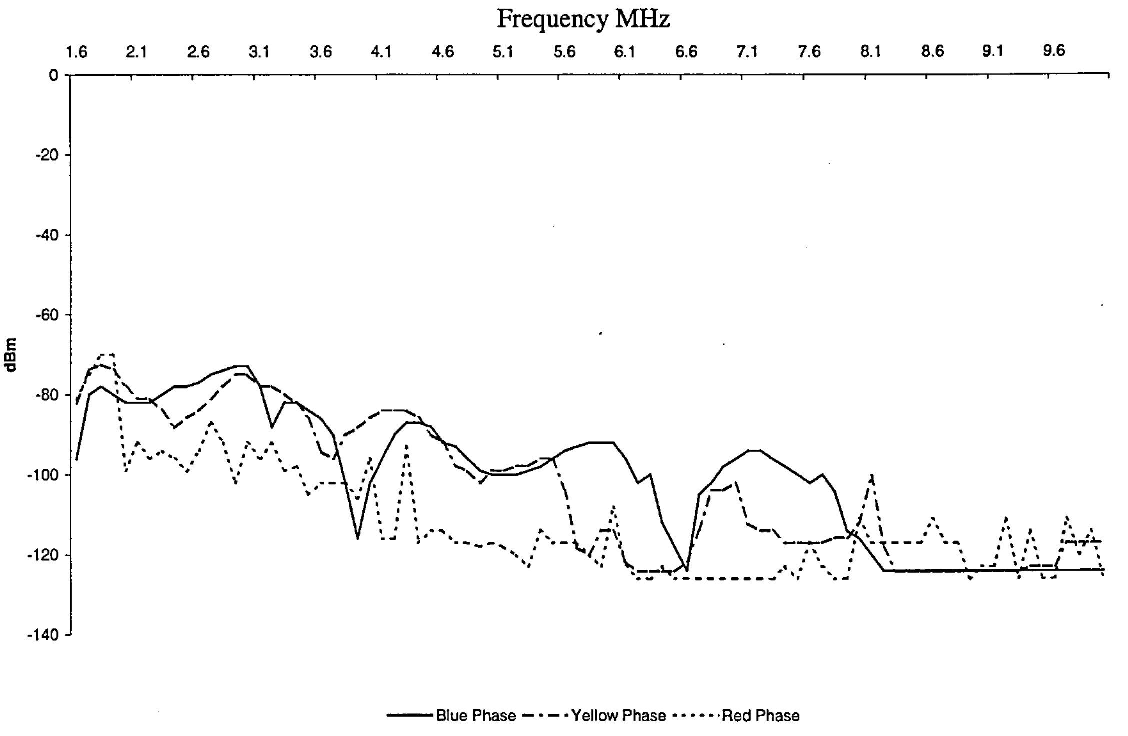


Figure 4.12: Plotted results from table 4.2

The characteristic noise floor at number 30 Applerigg followed a similar trend to that obtained at the substation but was approximately 10 db lower. As the number of test locations increased along Applerigg, similar results were obtained. Indeed the author has observed the same characteristics on networks in a number of European countries.

Noise plots were obtained throughout the duration of testing on the Kentrigg network, and although the time, day and season changed, in general the noise floor for each phase at a particular location remained below –65 dBm, or 0.32 nW. There was however a ten-minute period each day when broadband noise did affect the network. This was associated with the warm-up period of street lighting. Once the lights settled down to their normal operating efficiency the noise disappeared. In the UK, Sodium discharge lamps are the preferred option for community lighting, and this warm-up period is typical. The author has carried out similar tests in other European countries where Sodium discharge lamps were not used, and did not observe the same broadband interference. It should also be noted that UK street lighting tends to be fed from the same low voltage distribution network that supplies the domestic market. In the rest of Europe, street lighting tends to be fed from the same substation but via a separate network.

Figure 4.13 shows two traces of the noise floor for blue phase in the research hut, taken in August and November 1992. Results were recorded every 500 kHz, hence the blocky appearance.

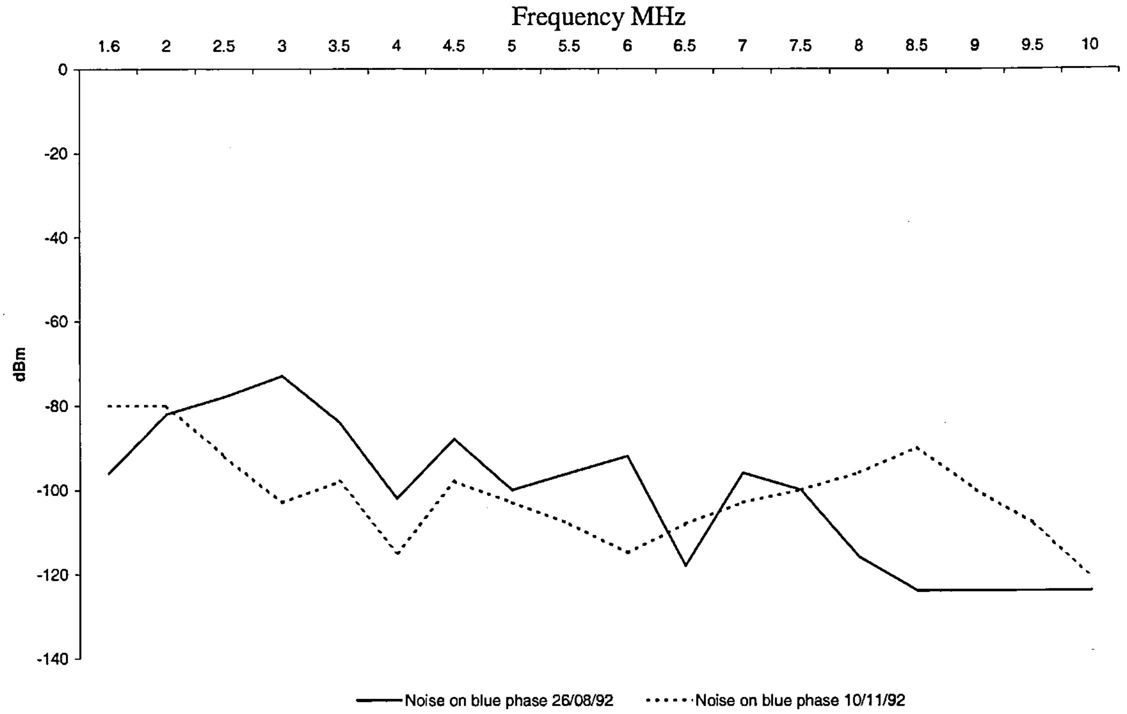


Figure 4.13: Noise floor on blue phase recorded in the research hut on 26/08/92 and 19/11/92

One of the reasons for choosing the Kentrigg substation was due to the fact that it presented a typical UK low voltage distribution network. The typical length for a three-phase feeder cable is approximately 250 m, and number 30 Applerigg was at the end of one of the Kentrigg feeder cables, a distance of approximately 270 m from the substation. The initial noise results obtained from the network suggested that, so long as any received signal was greater that 0.32 nW, communications were possible across the whole of the 1.6 MHz to 10 MHz bandwidth. As the research progressed, tests on other networks provided similar results.

Higher power transient interference was also observed. Although these transients would affect power line communication signals, their duration was never long enough to cause concern. Locally generated switching transients, such as those generated by switching on fluorescent lighting, are a good example of this type of interference. This short-lived noise could be identified by a few crackles over an analogue voice circuit, or a few corrupted packets on a digital circuit, requiring retransmission of the affected packets.

In conclusion, it is contended that the level of noise observed over the entire research period, at a number of different substations, was at a far lower level and more predictable than at first expected. The decision to use frequencies above 1 MHz ensured that typical interference observed in the lower frequency CENELEC bands was either not present, or greatly reduced.

4.5.2 Network response to a transmitted signal

The noise results obtained from the Kentrigg network suggested that noise interference would not prove too onerous for power line communications. The next task was to investigate the level of signal attenuation, and hence determine the injected power requirements for a signal to be successfully received at the extremities of the network.

Initially, the two HF radio transceivers were used to prove that analogue voice communication was possible. One transceiver was connected to the conditioning unit in the garage of number 30 Applerigg, and the other connected to one of the coupling units in the research hut.

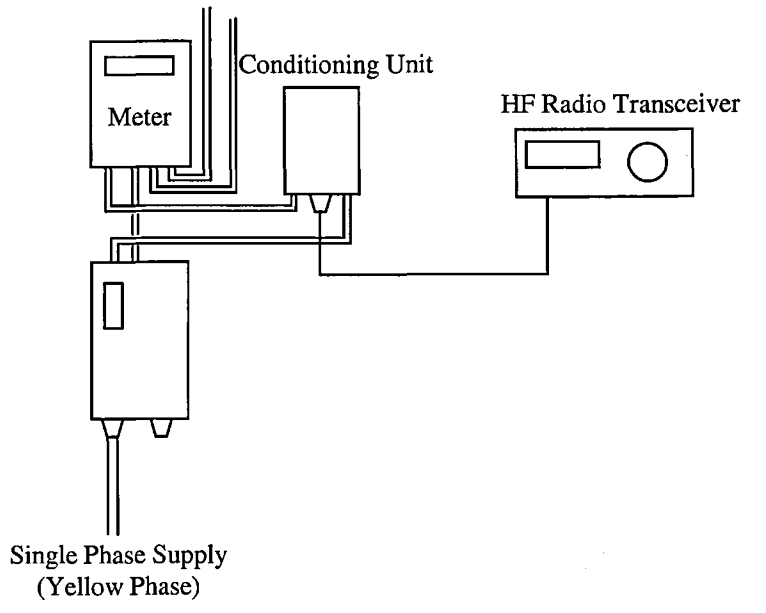


Figure 4.14: Test set up at number 30 Applerigg

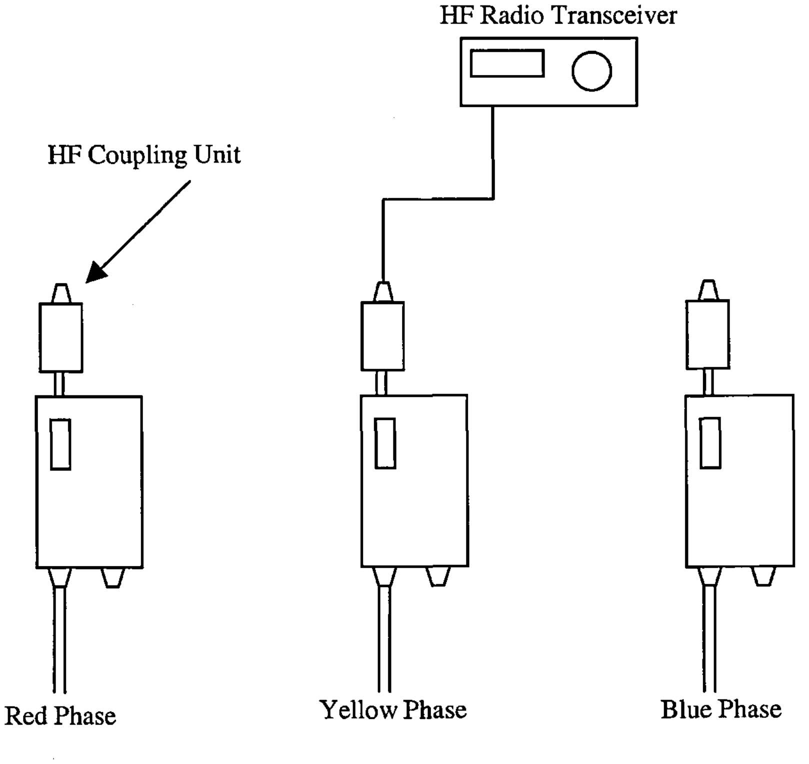


Figure 4.15: Test set up in the research hut

Clear reception was noted across the entire frequency range. All three phases in the research hut were used, and the clear results at number 30 suggested a high level of cross-talk between phases. The power levels used for the injected signals were progressively reduced, to determine the minimum level required for successful communications. It was soon established that the lowest power setting on the transceivers was still too high and further attenuation was required via a variable attenuation block connected to the receiving end transceiver. With an equivalent injected power of 1 μW, voice communications were still possible between the research hut and number 30 Applerigg.

The transceivers had three modes of operation: Single Side-band (SSB), Amplitude Modulation (AM) and narrow-band Frequency Modulation (FM). All three modes were tried but FM was chosen as the preferred modulation method, largely due to its stability in the presence of noise on the low voltage distribution network, most of which was AM in nature.

Early tests had indicated that decreasing the power of the injected signal produced a linear reduction in signal strength at the receiving end, i.e. reducing the transmitted power by 3 dB resulted in a 3 dB reduction at the receiving end. Further tests indicated that an injected signal of approximately 1 mW (0 dBm) provided an acceptable response, and was therefore chosen as a benchmark for all network testing. If a signal was injected at 30 Applerigg with a power of approximately 1 mW, an acceptable signal-to-noise ratio was achieved at the receiving end across the frequency range 1.6 MHz to 10 MHz. Figure 4.16 shows a typical set of results. A noise plot is also included, to indicate the available signal headroom.

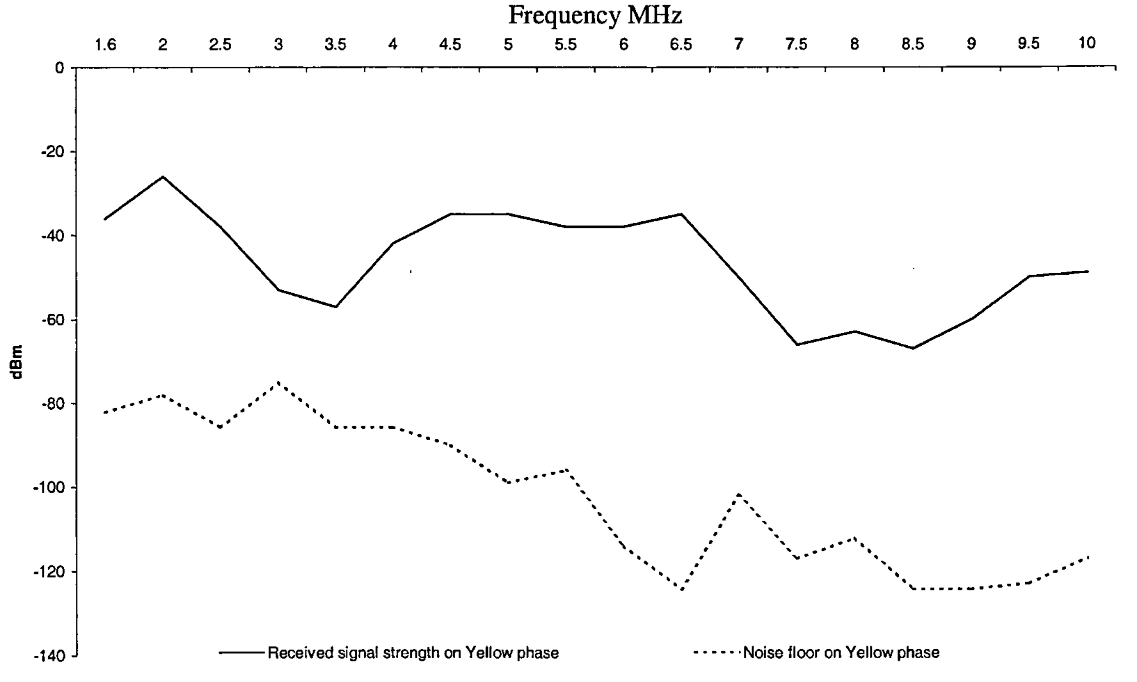


Figure 4.16: Signal attenuation characteristics between 30 Applerigg and the research hut

Although signals were injected onto a single phase, a large amount of cross-talk was observed between phases. Due to the close proximity of the phase conductors in a low voltage distribution feeder cable, the complexity of the network architecture, and the transmission characteristics of the injected signals, the signal power at the receiving end would vary across all three phases. Indeed, at any particular frequency, if a signal was injected at number 30 Applerigg (number 30 Applerigg was connected to yellow phase), the best response was not necessarily obtained from yellow phase in the research hut. Figure 4.17 shows the results of a 1 mW signal injected on yellow phase at number 30 Applerigg and received on yellow and then blue phases in the research hut. It can be seen that at some frequencies, a stronger signal is obtained on blue phase, although overall the best results are obtained from yellow phase.

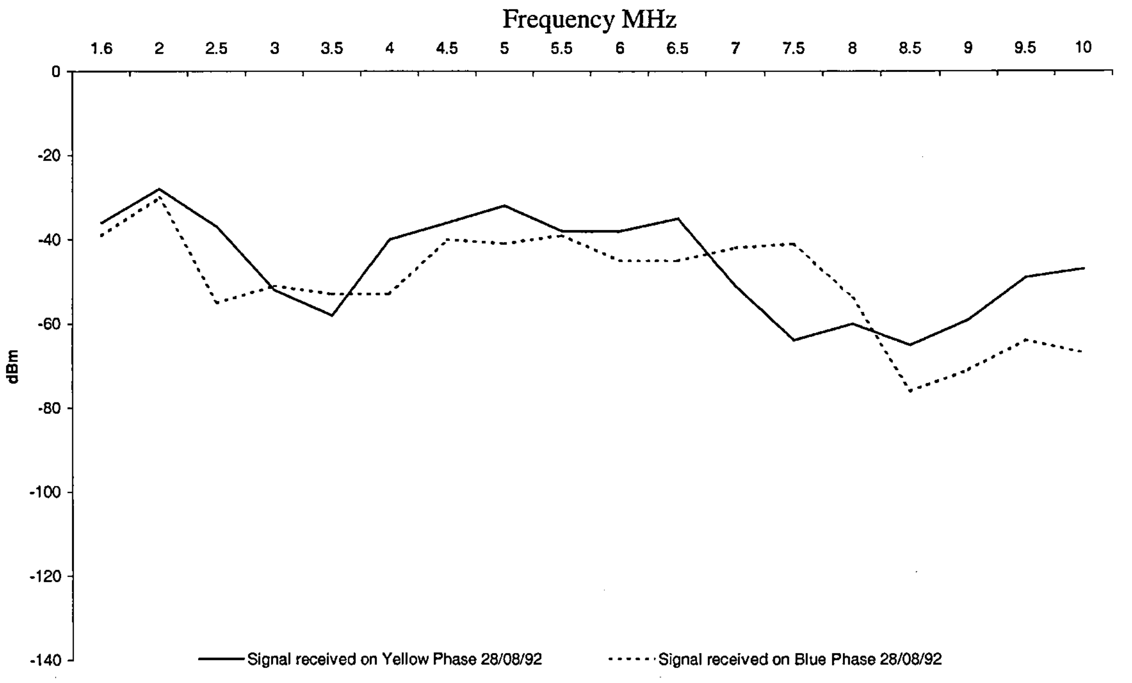


Figure 4.17: Strength of signals received in the hut on Yellow and Blue Phases

The reciprocal nature of the network was also tested, the transmitting and receiving ends were reversed and the results compared. Figure 4.18 contains a typical set of results showing the received power levels at 30 Applerigg and the research hut. The difference in the traces can be accounted for by the fact that non-standard test equipment was being used. It was difficult to guarantee the accuracy of the transmitted power or the received power level as indicated on the S-meter. Within the parameters of the work being undertaken these errors were not unreasonable; the attenuation trend over the frequency range of interest can easily be identified from the results obtained.

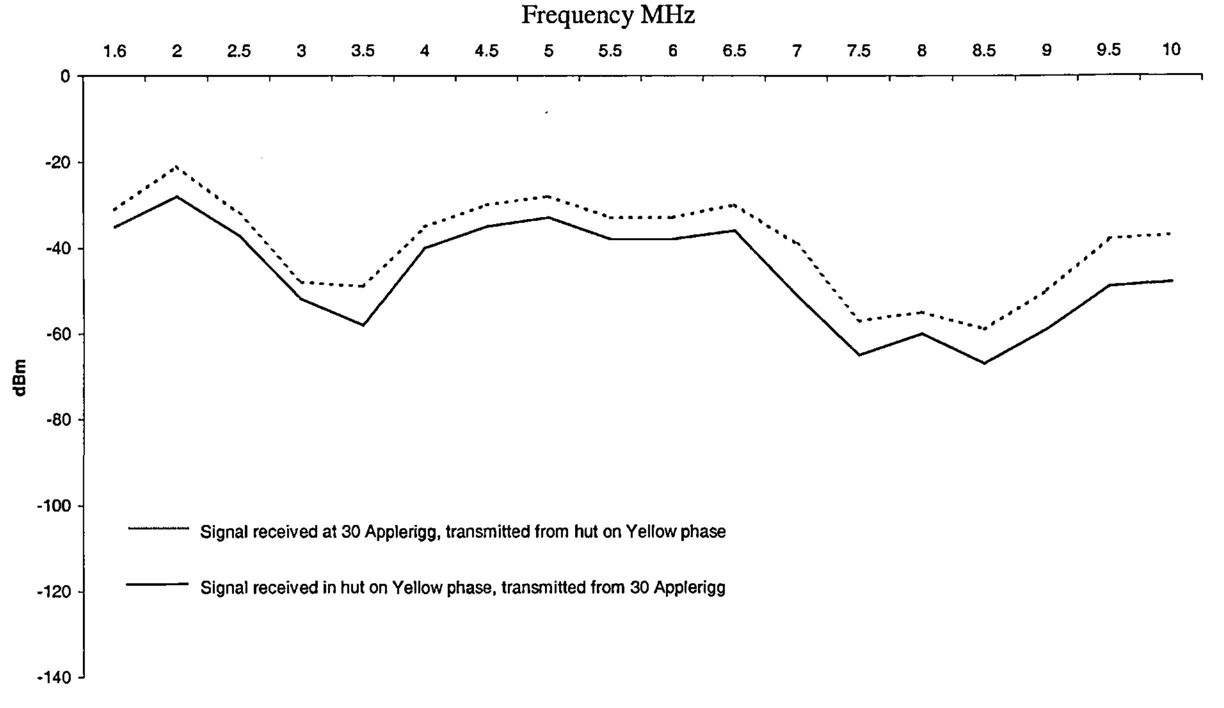


Figure 4.18: Results of reciprocal tests on the Kentrigg network 28/08/92

In order to guarantee an acceptable level of service for any power line product, the stability of the network over time must be understood and accounted for. Ideally the network should have little or no change in its signal attenuation characteristics. To determine the situation between 30 Applerigg and the research hut, the following test was repeated throughout the period of network testing in Kendal. A signal of approximately 1 mW was injected onto yellow phase at 30 Applerigg across the frequency range of interest. The strength of the received signal was recorded on yellow phase in the research hut. Whilst the network remained unchanged the results from the Kentrigg network remained very predictable. Figure 4.19 shows two sets of results, obtained on 26/08/92 and 04/09/92.

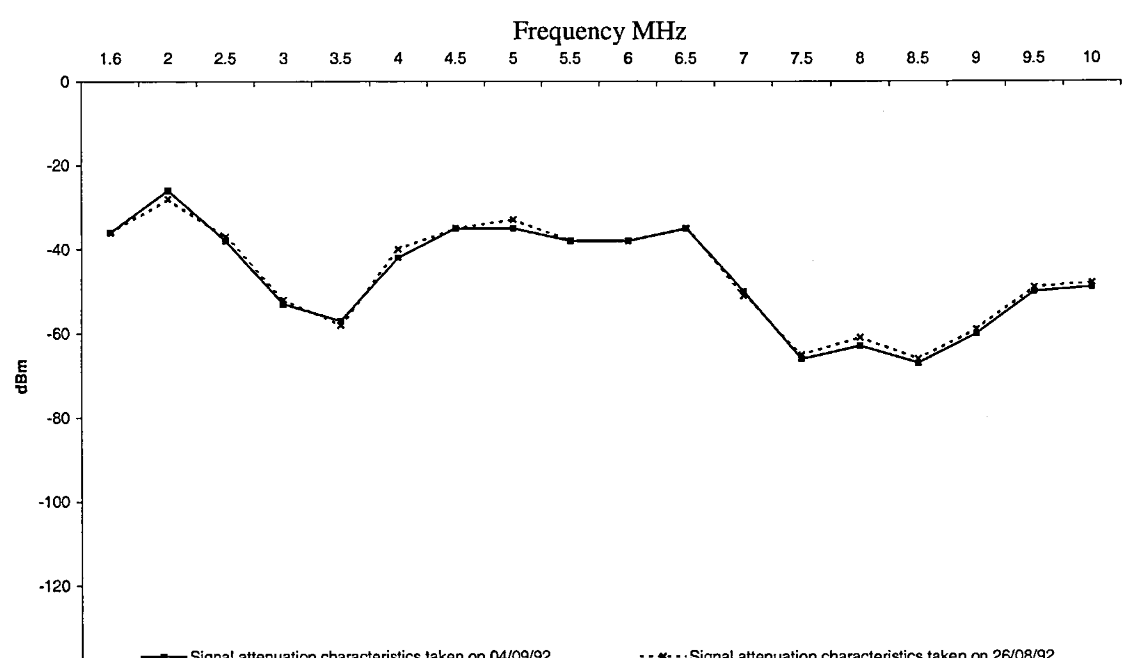


Figure 4.19: Signal attenuation characteristics between 30 Applerigg and research hut

Signal attenuation tests were also carried out up to 31 MHz in order to observe the attenuation trend at higher frequencies. Figure 4.20 shows the level of signal attenuation between 30 Applerigg and the research hut, in the frequency range 1.6 MHz to 31 MHz.

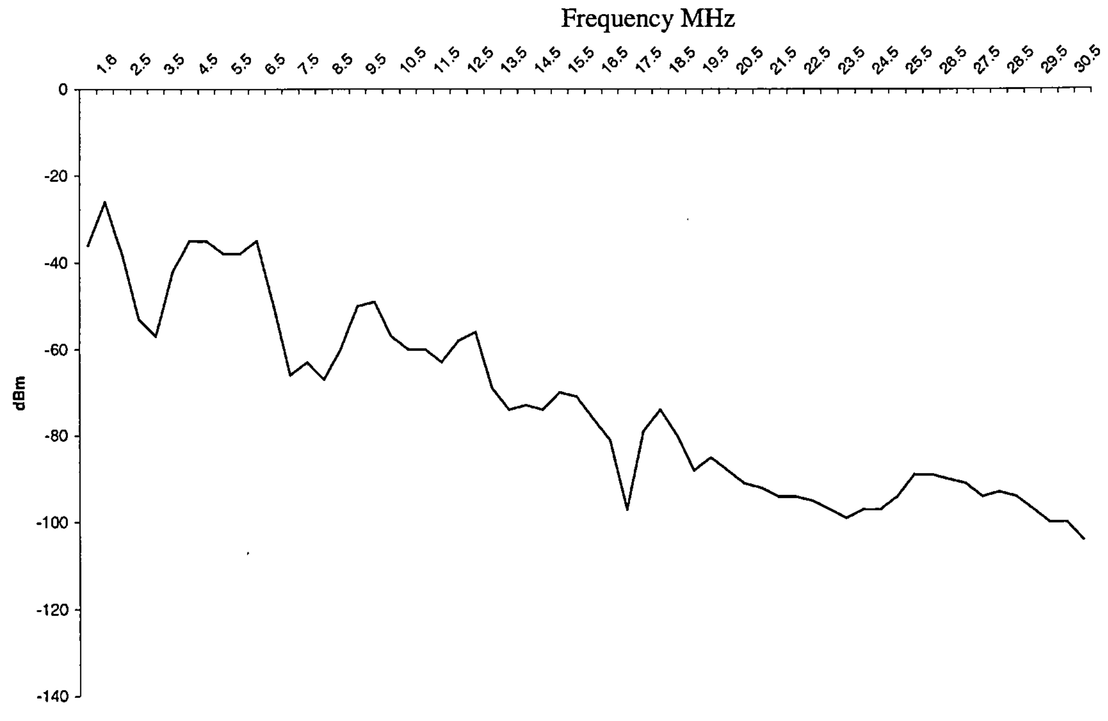


Figure 4.20: Signal attenuation between 30 Applerigg and the research hut in the frequency range 1.6 MHz to 31 MHz

The test environment between 30 Applerigg and the research hut was made available in the fourth quarter of 1992, and many of the research techniques were developed using these two locations. The research group hoped to include the whole of Applerigg in the programme of work, and so once the domestic Conditioning Unit design was finalised, and had passed NOREWB's safety requirements, the residents of Applerigg were contacted and invited to participate in the project. All except one responded positively. Conditioning Units were hand-made, so the installation process was spread over a four-month period between March and June 1993. Tests, similar to those already described, were carried out at each location and the results used to build up a signal attenuation picture for the Kentrigg network. The results confirmed the belief that by using an injected signal strength of 1 mW, all houses on Applerigg could receive a signal with adequate headroom.

The following pages from 143 to 154 inclusive, contain signal attenuation characteristics for each of the participating properties along Applerigg. The plots indicate at which house the results were obtained, the electrical phase supplying the house, and the date the results were obtained. Signals were injected onto each phase in turn in the research hut.

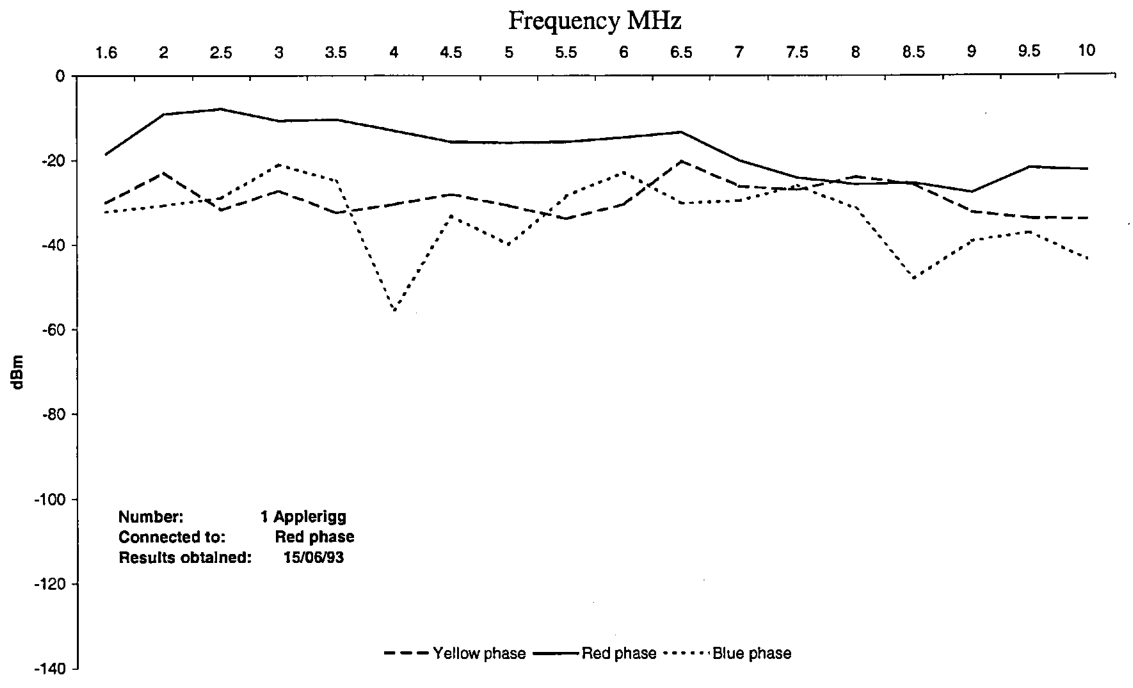


Figure 4.21: Attenuation characteristics for number 1 Applerigg

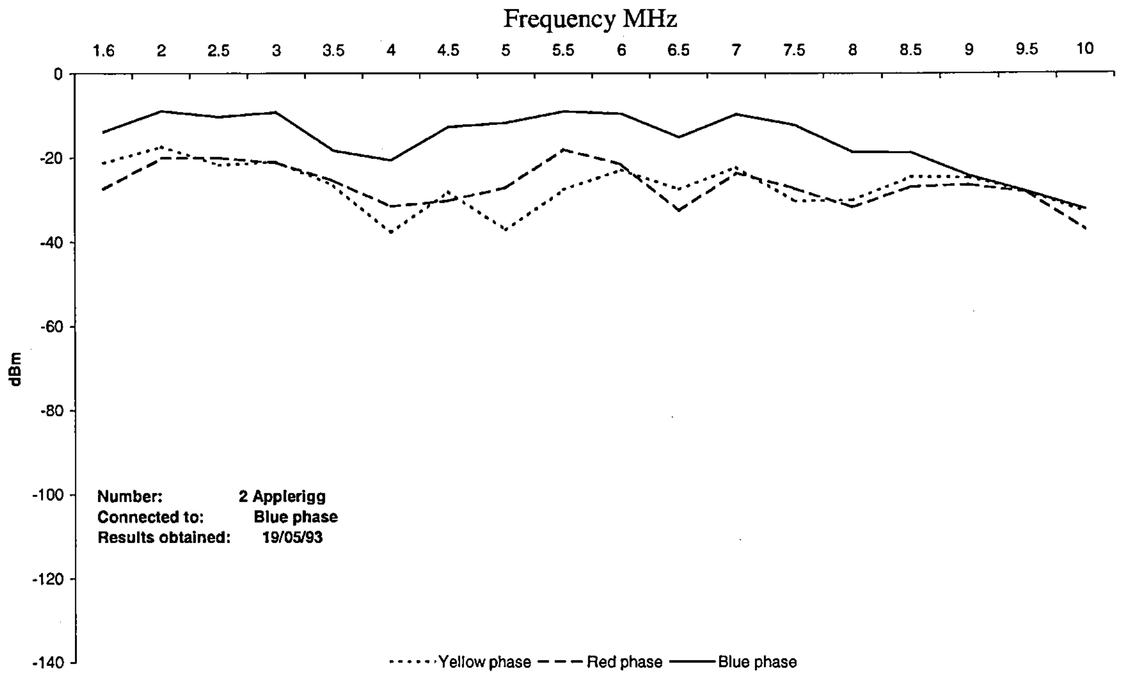


Figure 4.22: Attenuation characteristics for number 2 Applerigg

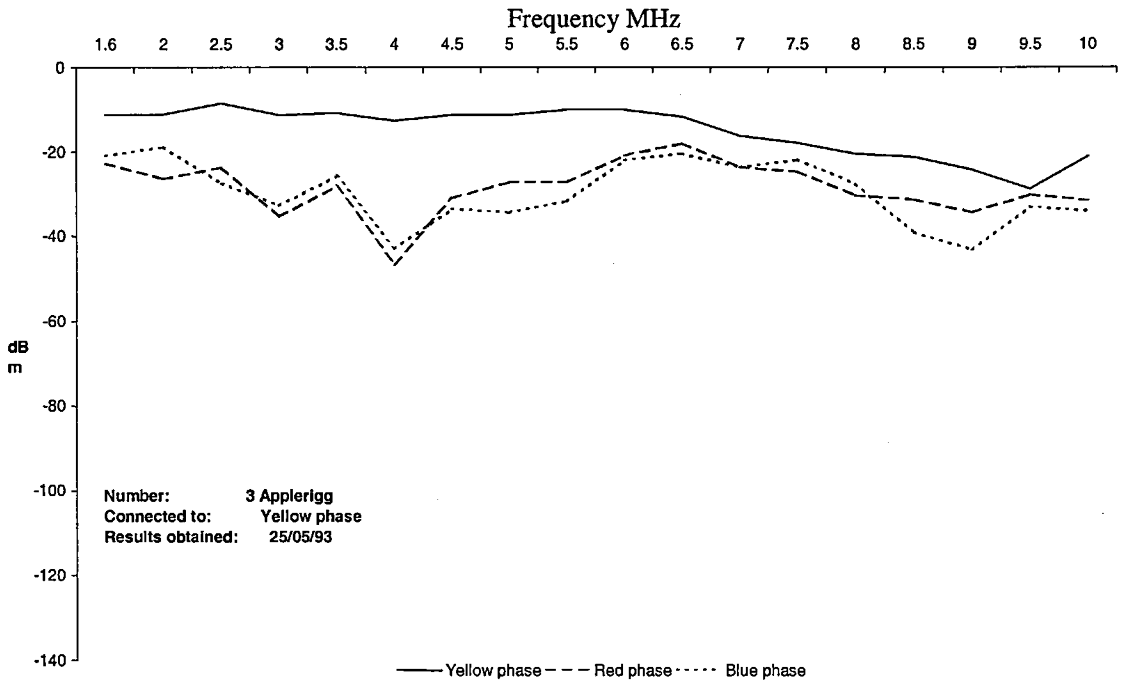


Figure 4.23: Attenuation characteristics for number 3 Applerigg

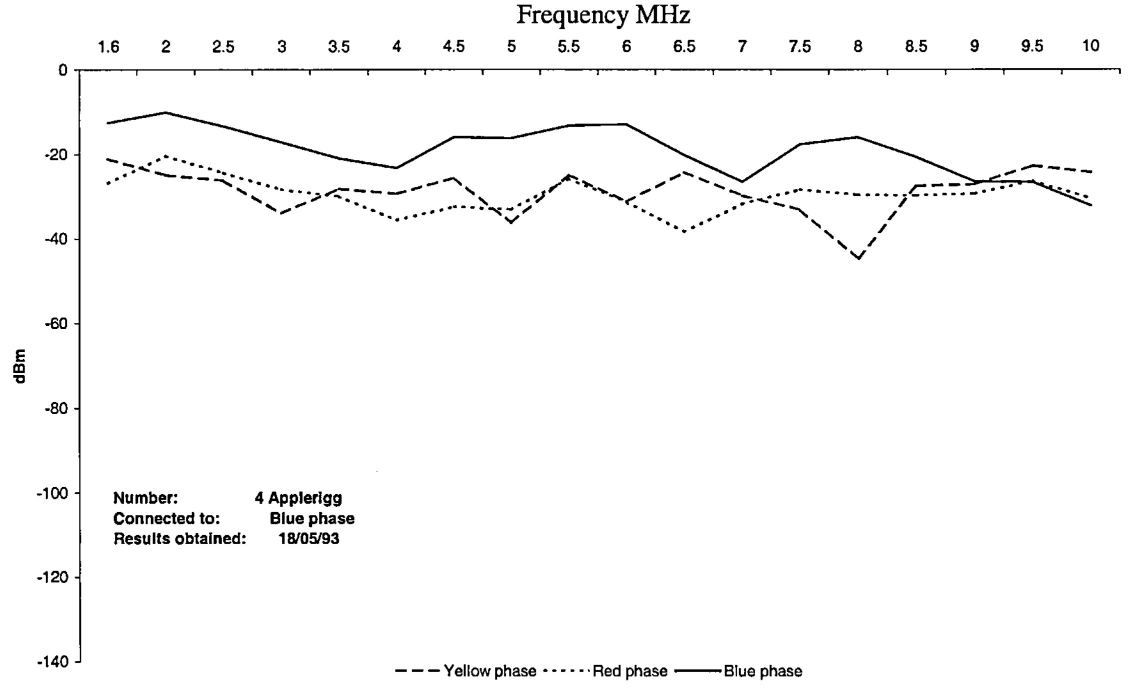


Figure 4.24: Attenuation characteristics for number 4 Applerigg

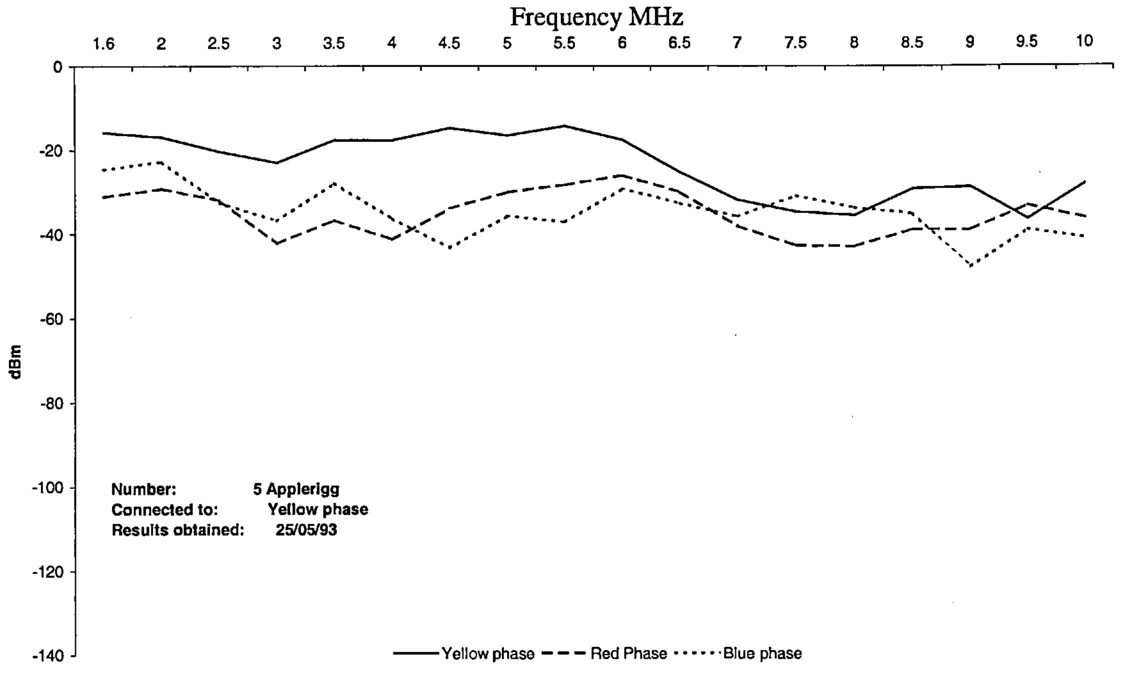


Figure 4.25: Attenuation characteristics for number 5 Applerigg

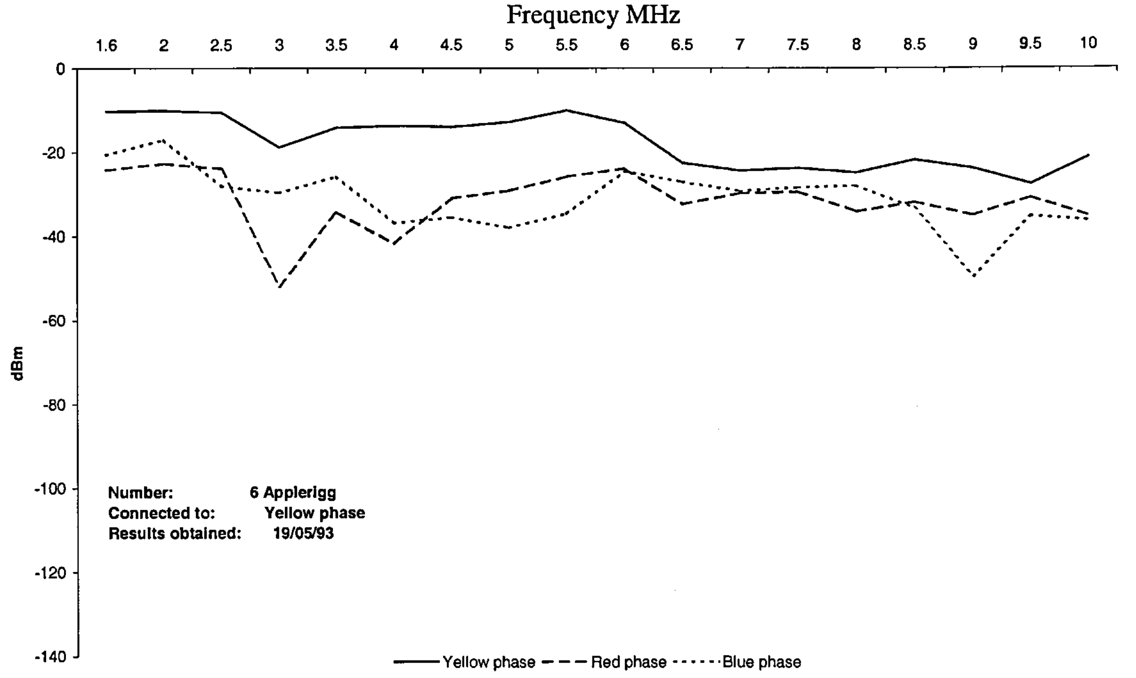


Figure 4.26: Attenuation characteristics for number 6 Applerigg

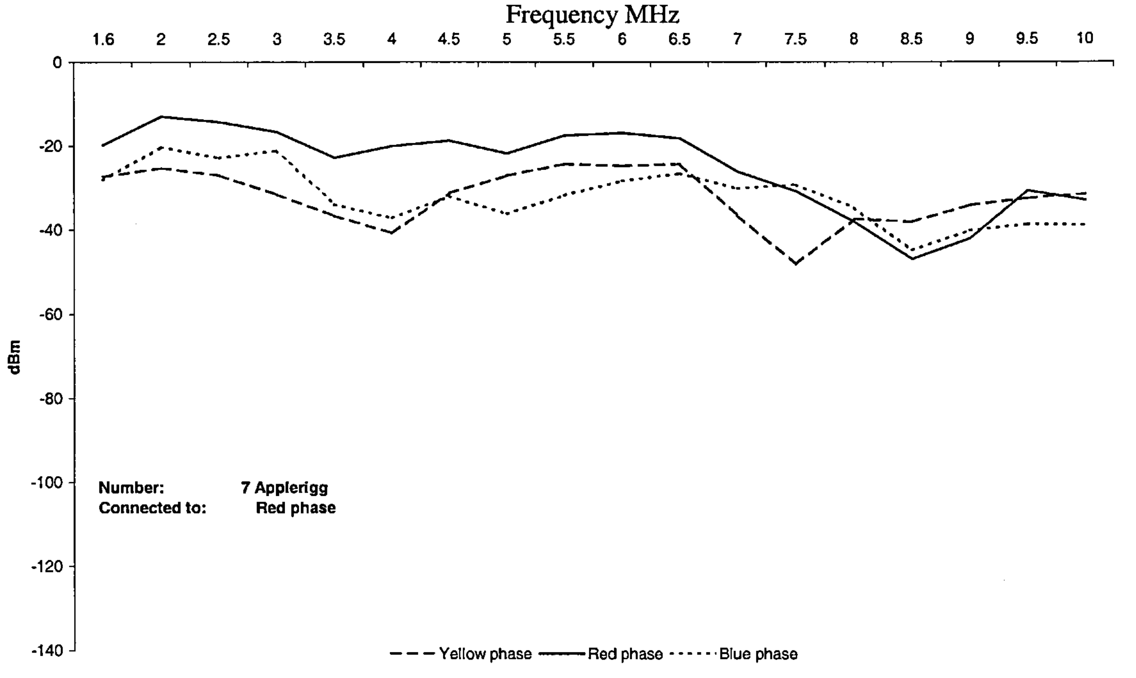


Figure 4.27: Attenuation characteristics for number 7 Applerigg

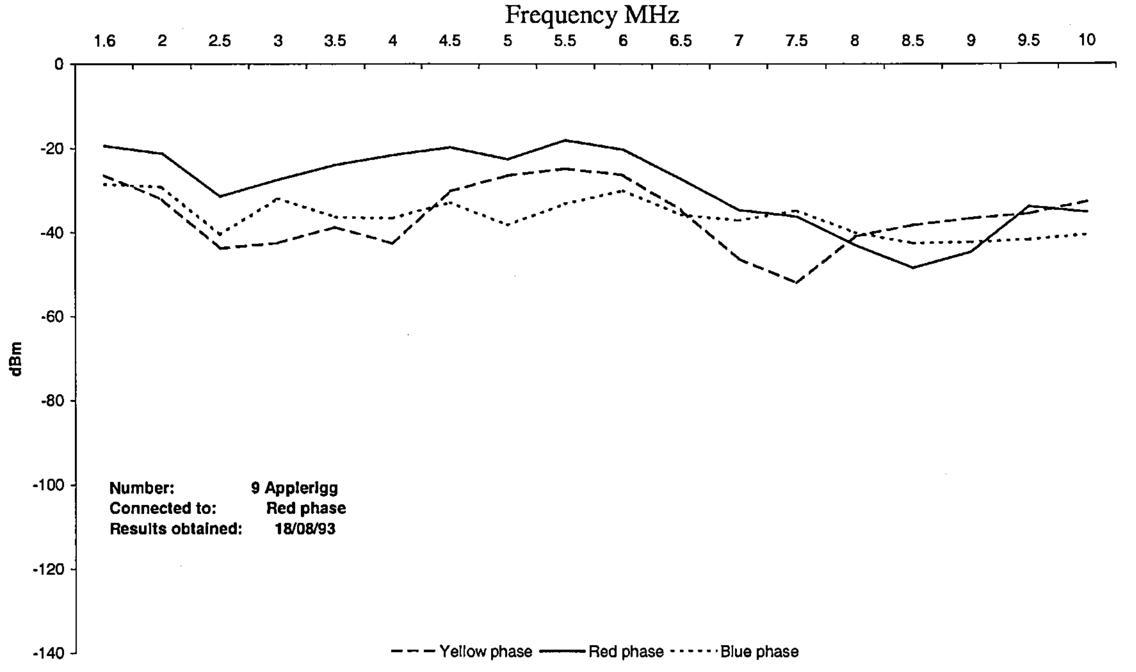


Figure 4.28: Attenuation characteristics for number 9 Applerigg

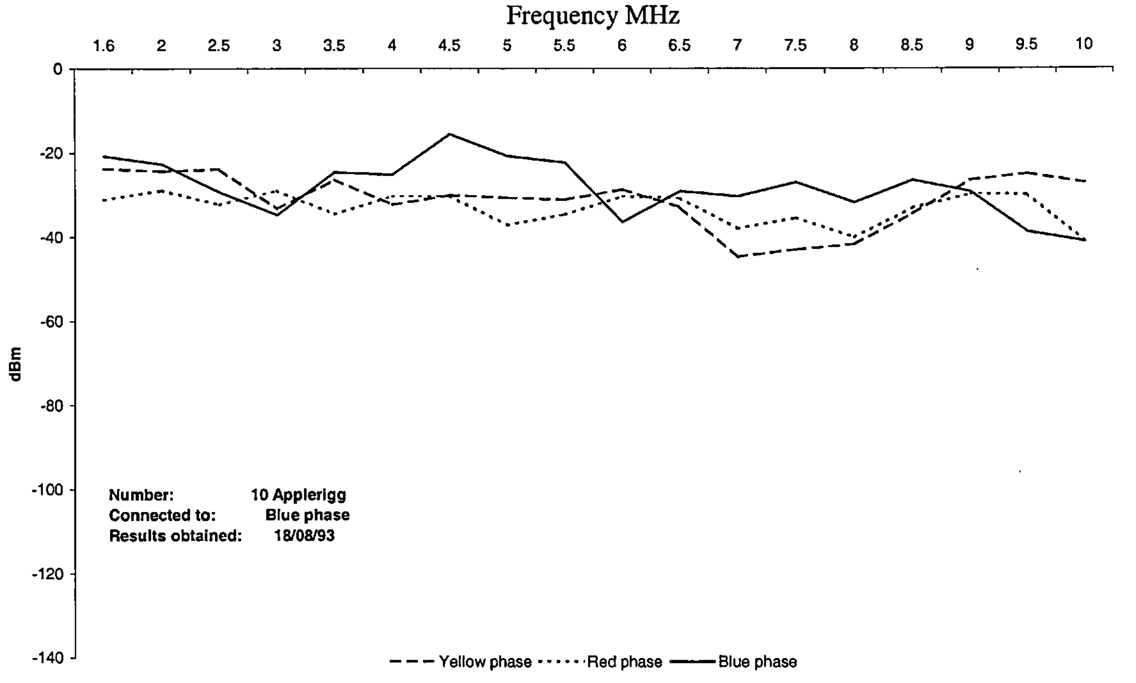


Figure 4.29: Attenuation characteristics for number 10 Applerigg

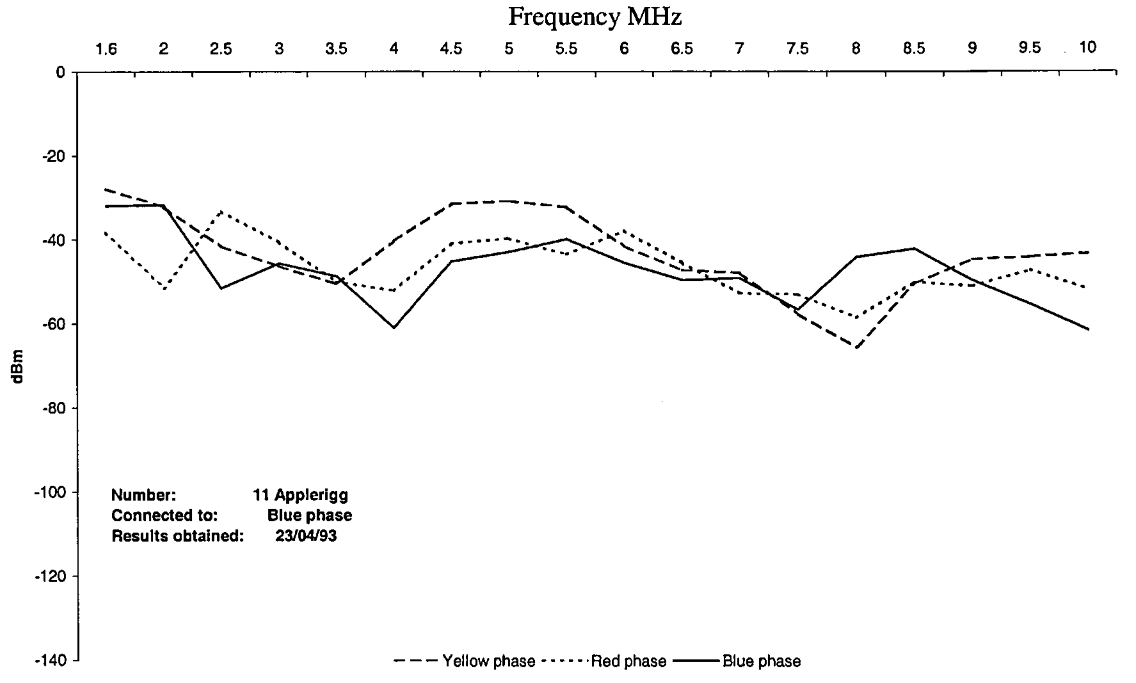


Figure 4.30: Attenuation characteristics for number 11 Applerigg

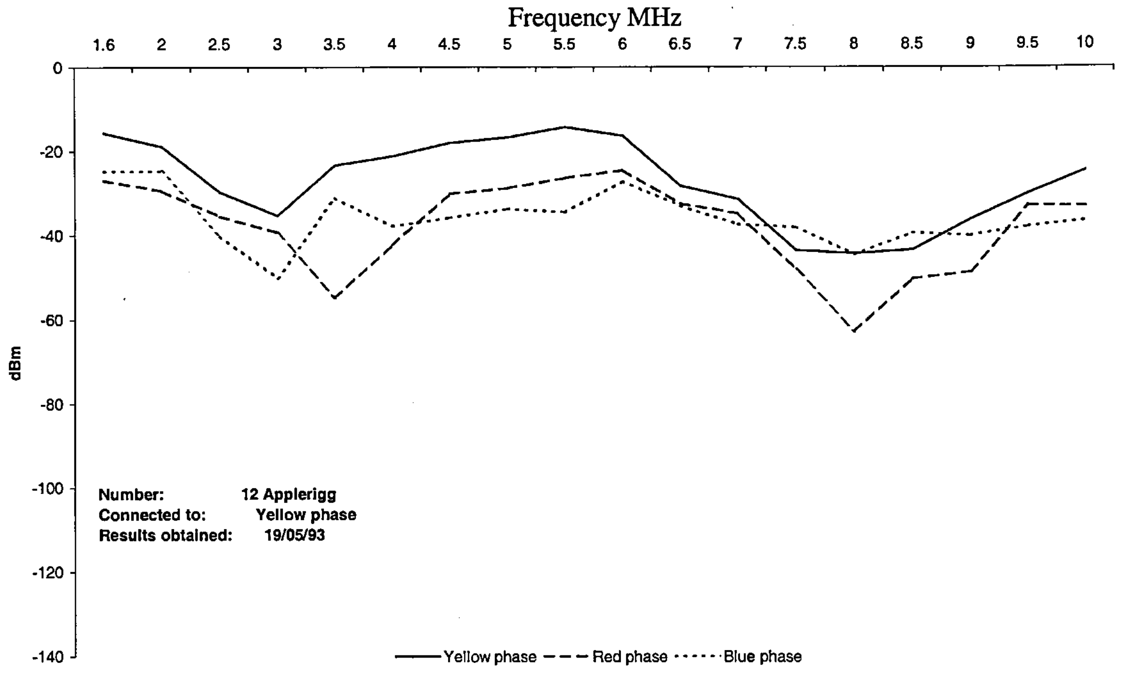


Figure 4.31: Attenuation characteristics for number 12 Applerigg

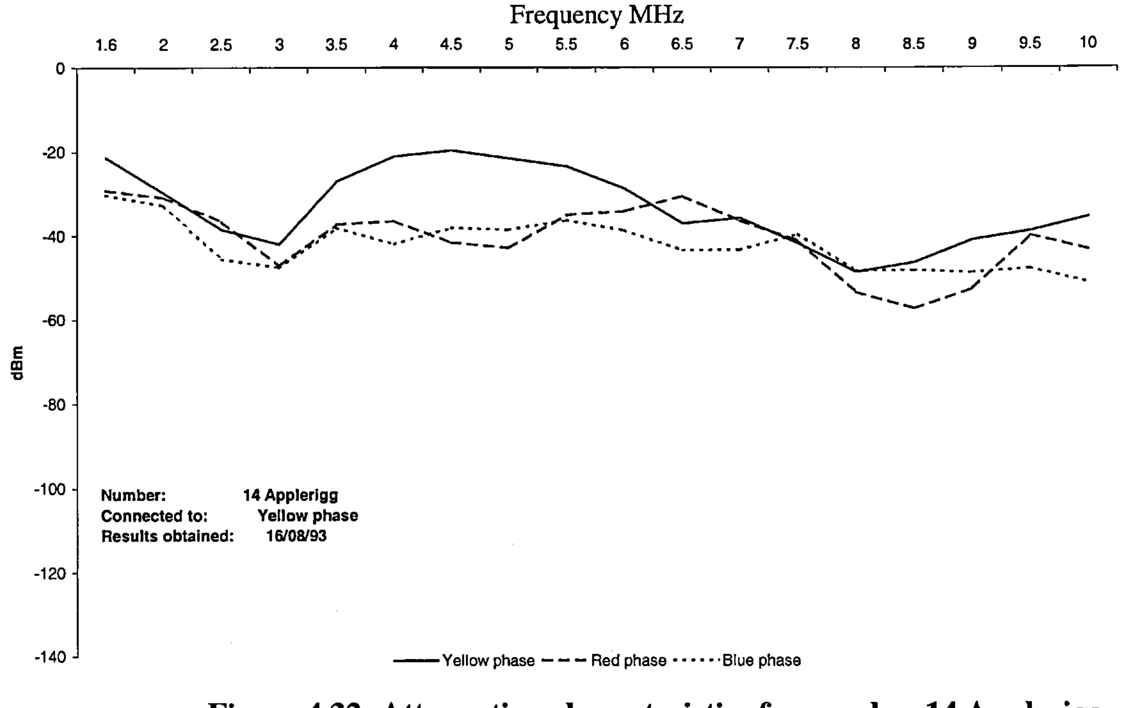


Figure 4.32: Attenuation characteristics for number 14 Applerigg

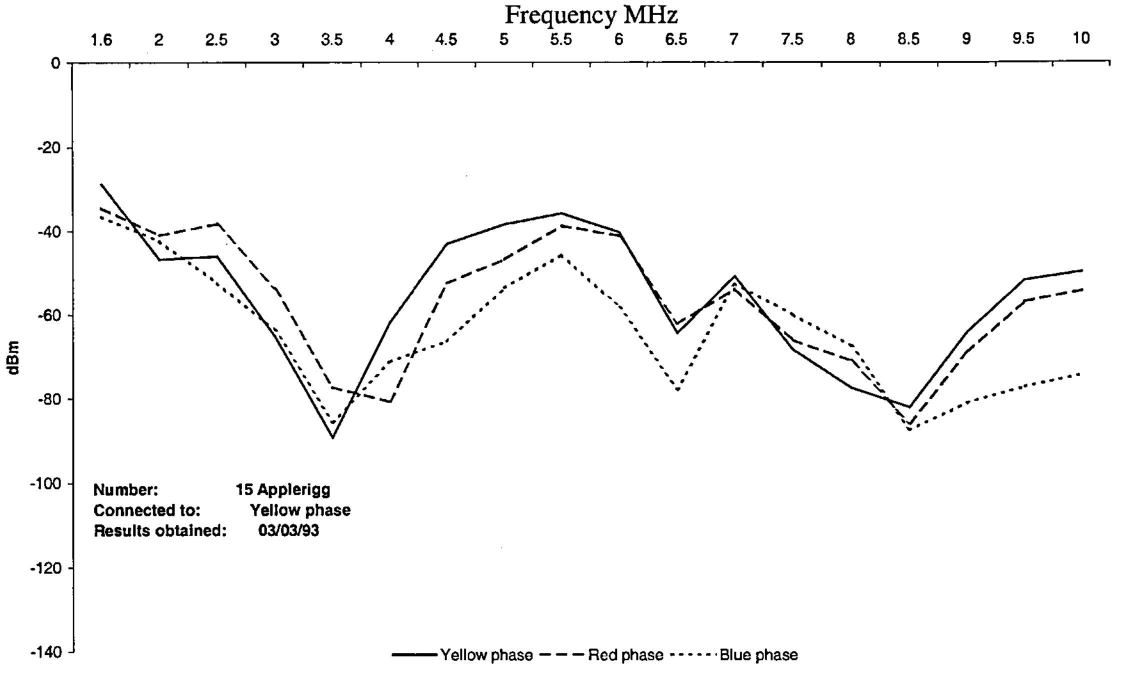


Figure 4.33: Attenuation characteristics for number 15 Applerigg

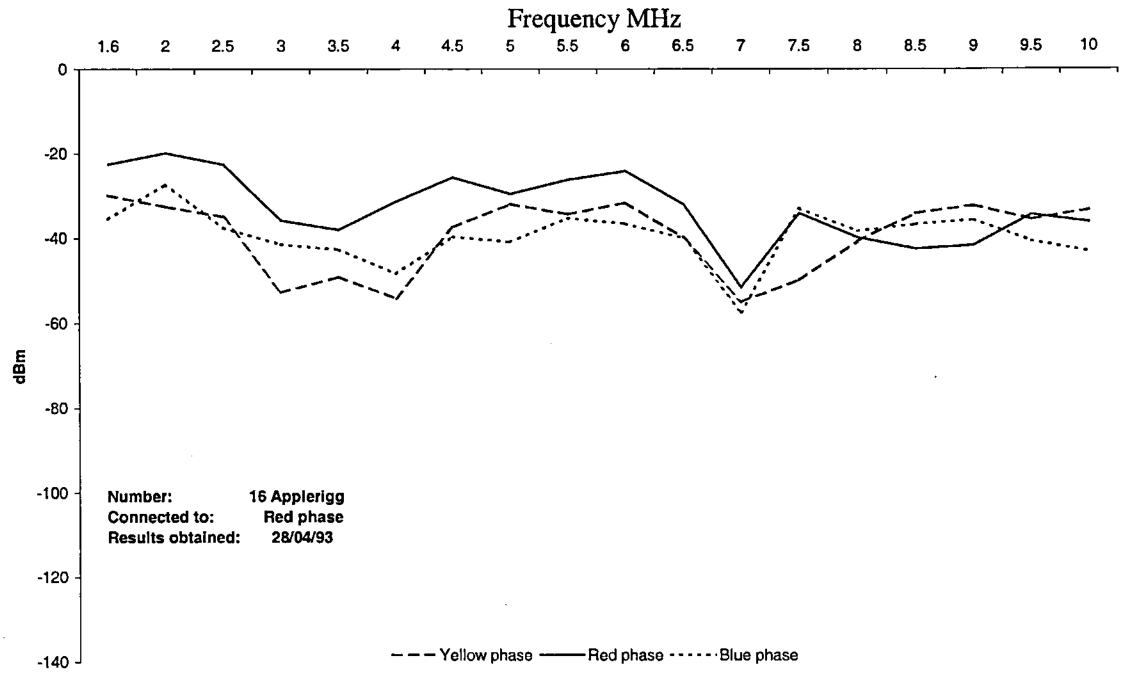


Figure 4.34: Attenuation characteristics for number 16 Applerigg

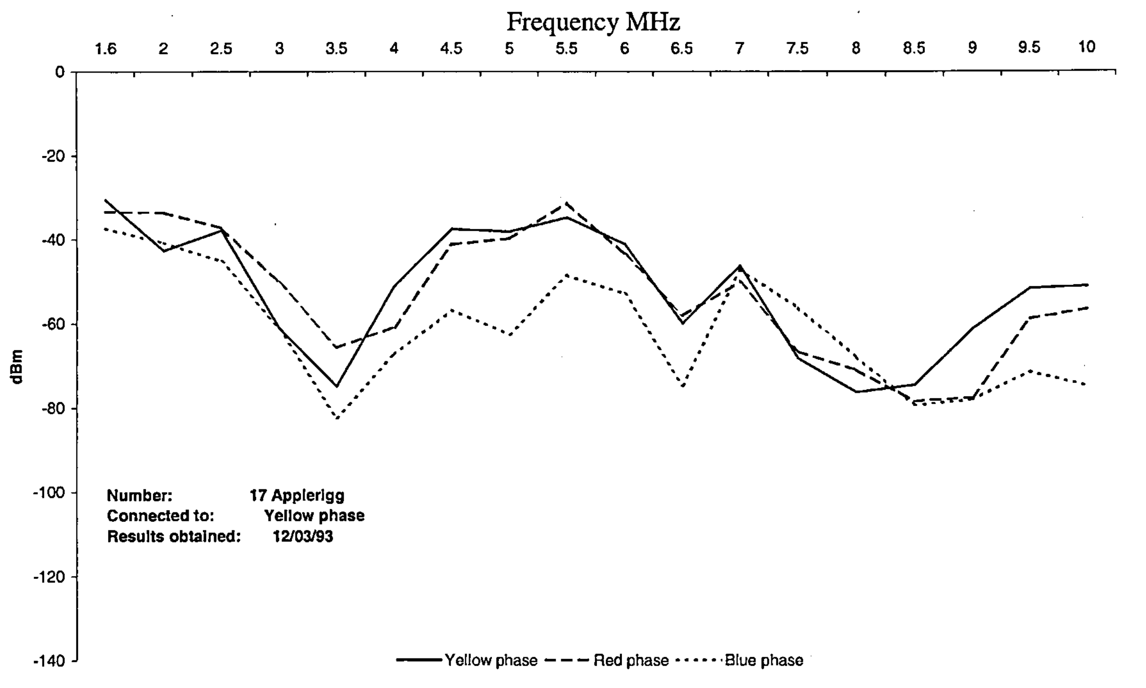


Figure 4.35: Attenuation characteristics for number 17 Applerigg

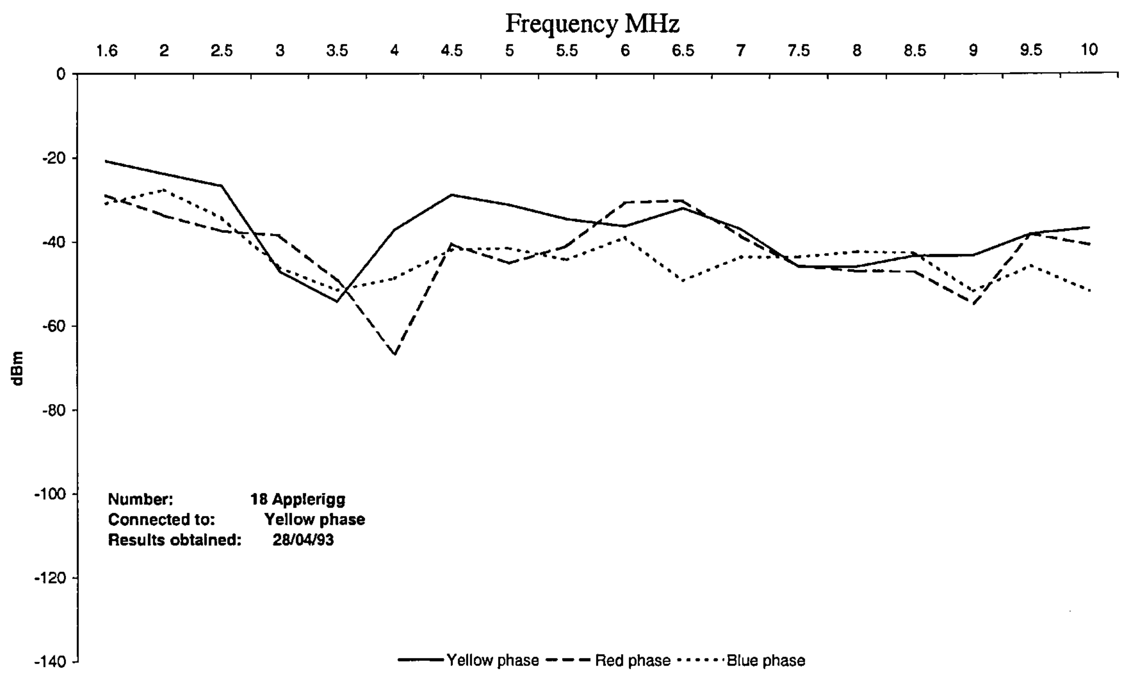


Figure 4.36: Attenuation characteristics for number 18 Applerigg

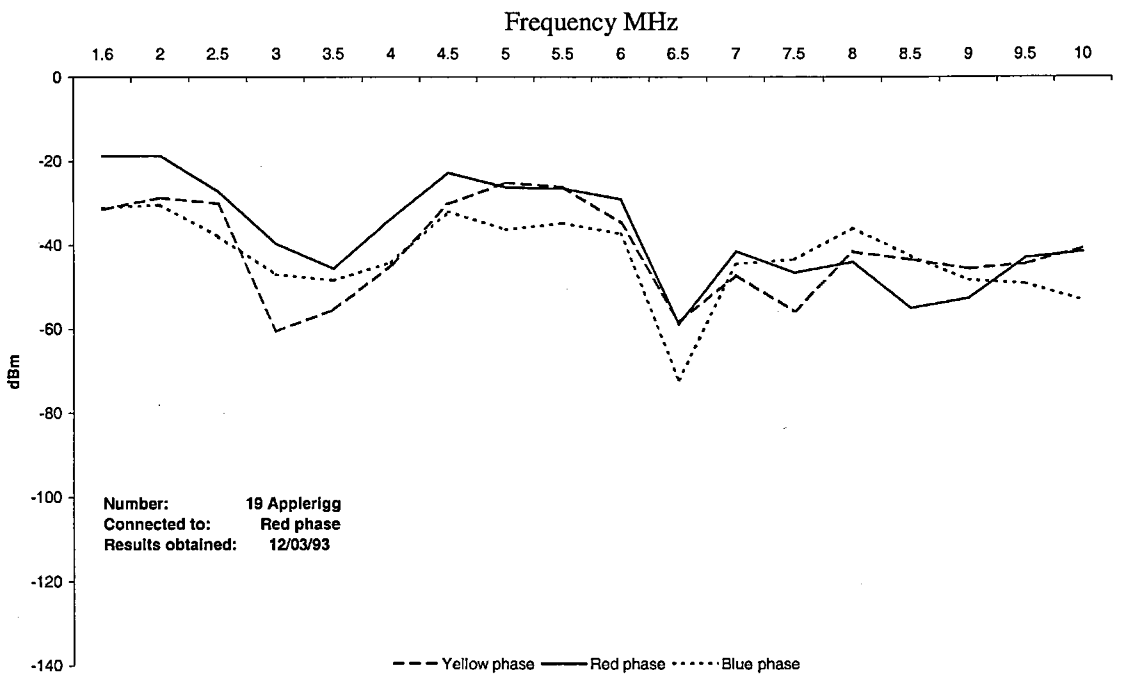


Figure 4.37: Attenuation characteristics for number 19 Applerigg

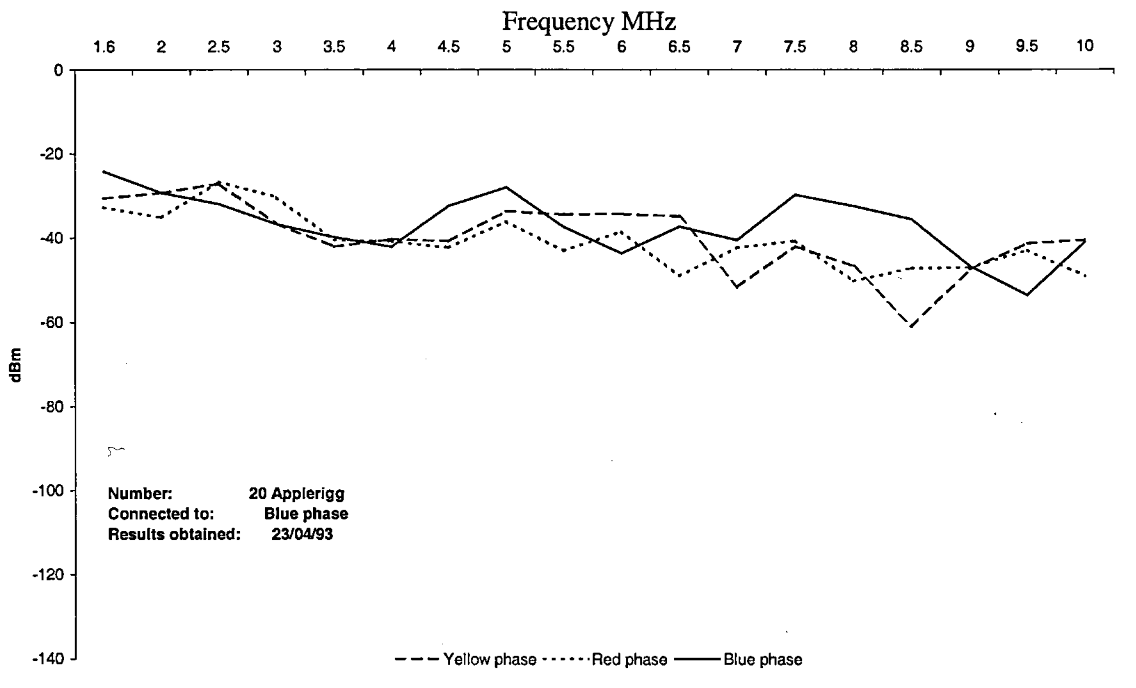


Figure 4.38: Attenuation characteristics for number 20 Applerigg

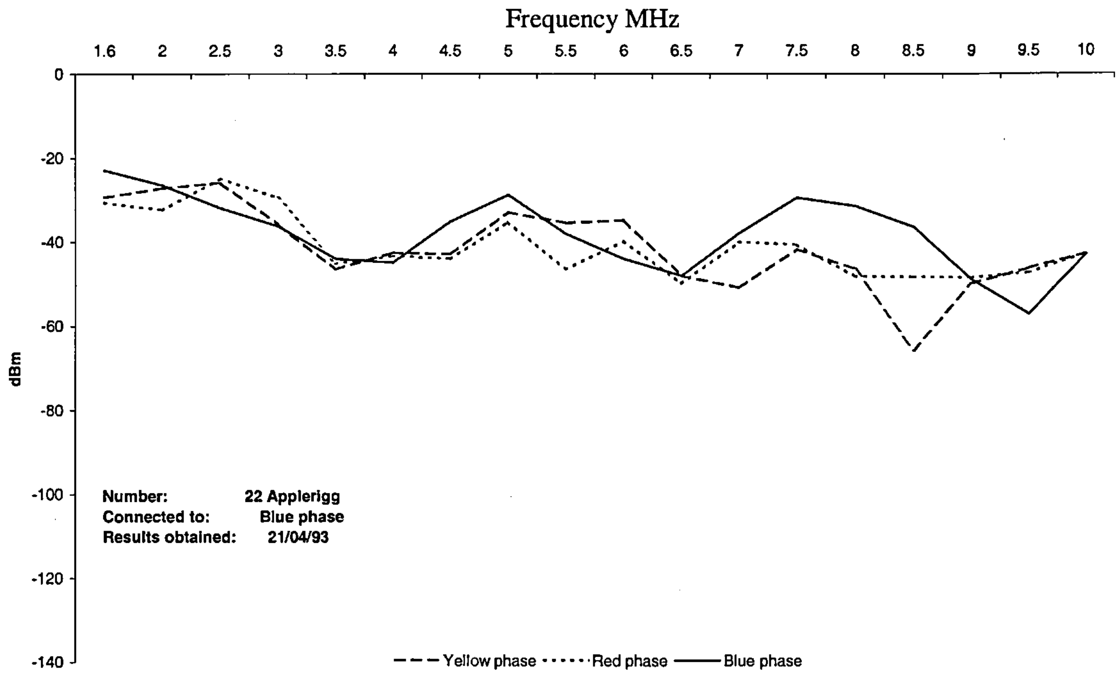


Figure 4.39: Attenuation characteristics for number 22 Applerigg

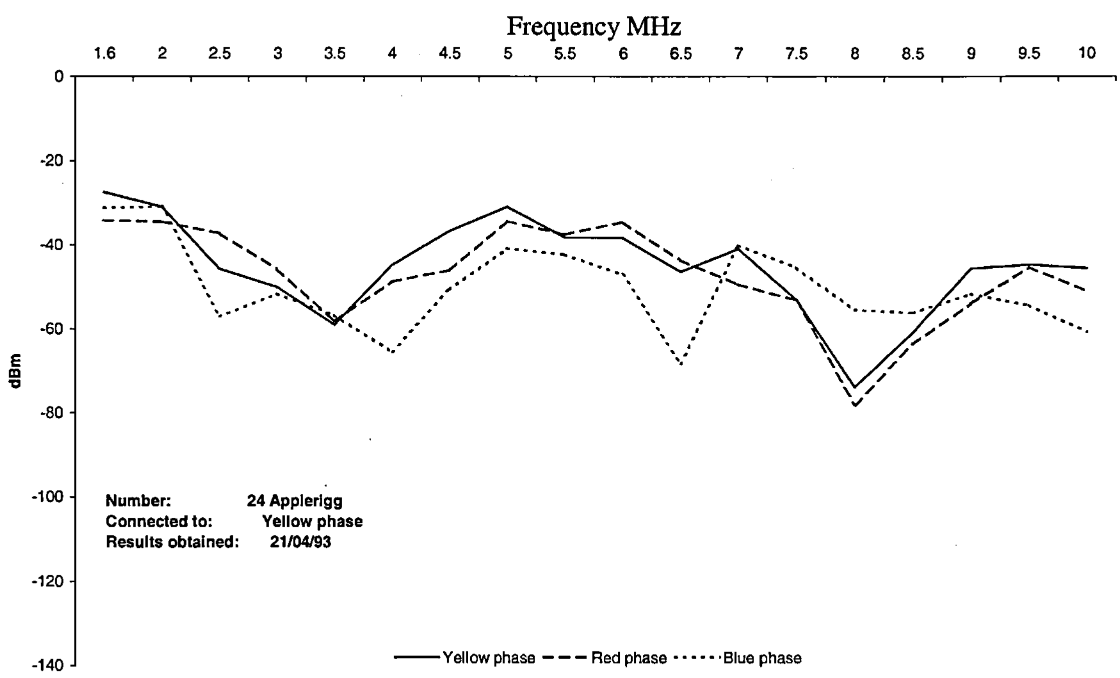


Figure 4.40: Attenuation characteristics for number 24 Applerigg

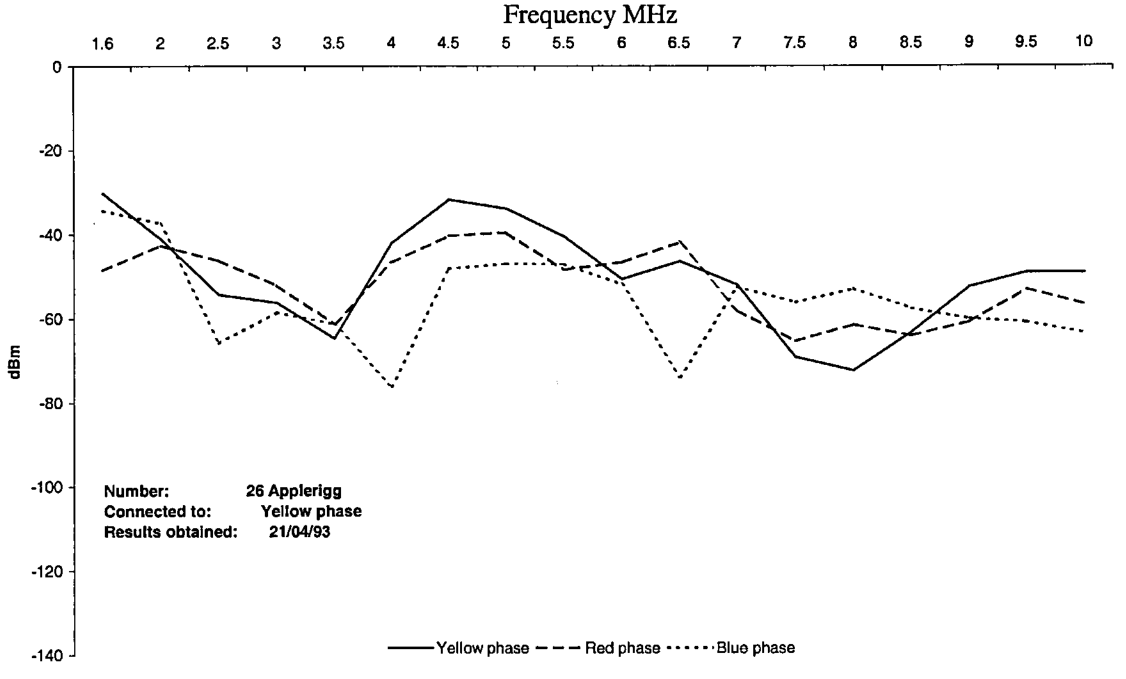


Figure 4.41: Attenuation characteristics for number 26 Applerigg

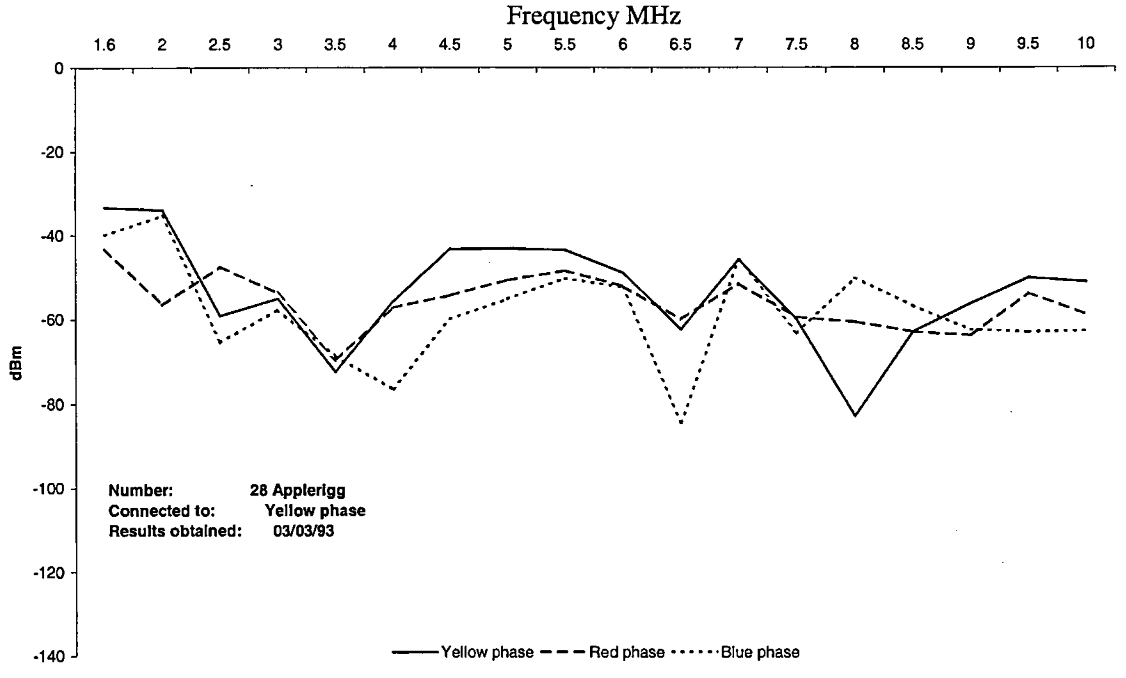


Figure 4.42: Attenuation characteristics for number 28 Applerigg

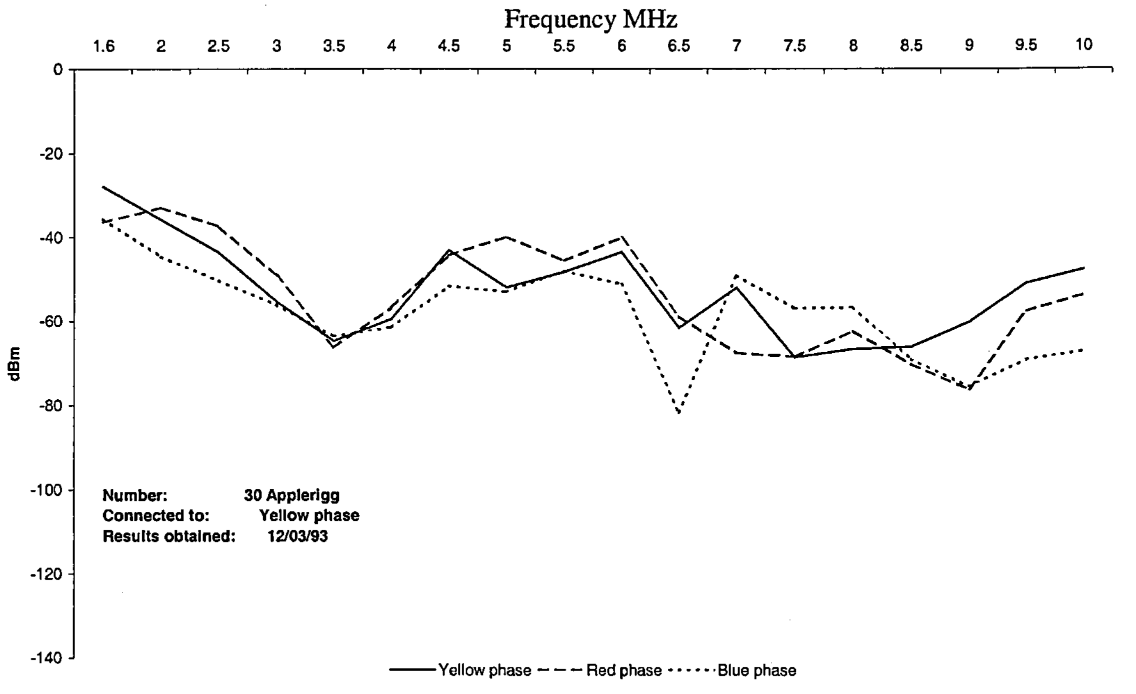


Figure 4.43: Attenuation characteristics for number 30 Applerigg

Tests were also carried out at the extremities of the Kentrigg network in two Link Boxes. Some three-phase feeder cables on a Low Voltage Distribution Network will terminate in a Link Box. A Link Box is a point where feeds from two separate substations meet and, if required, can be linked together. Under normal operating conditions the links are not installed and the two networks run independently. If essential maintenance work requires one substation to be disconnected from the network, or, if a fault has resulted in the loss of power to a section of network, links can be inserted in the Link Box in order to 'back-feed' the network.

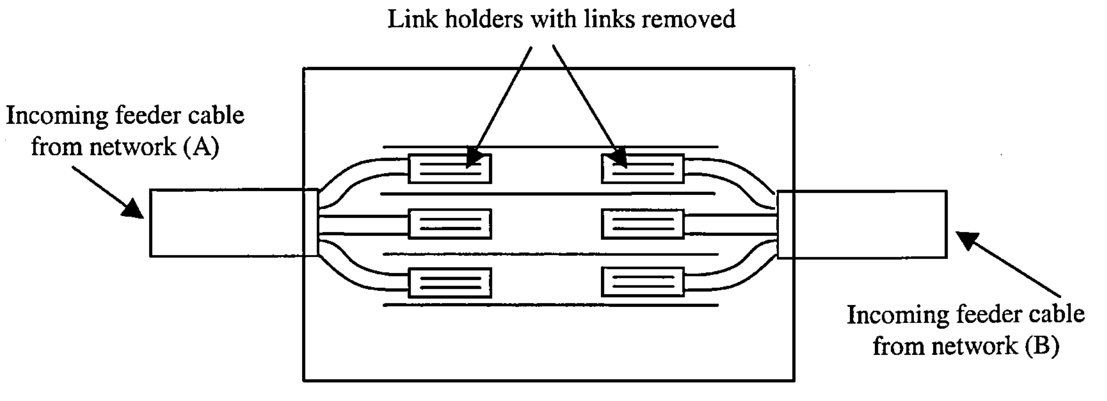


Figure 4.44: Typical Link Box configuration

With reference to figure 4.6 and figure 4.7, the following two graphs plot the results of a 1 mW signal injected in the research hut and received at link boxes 13 and 19.

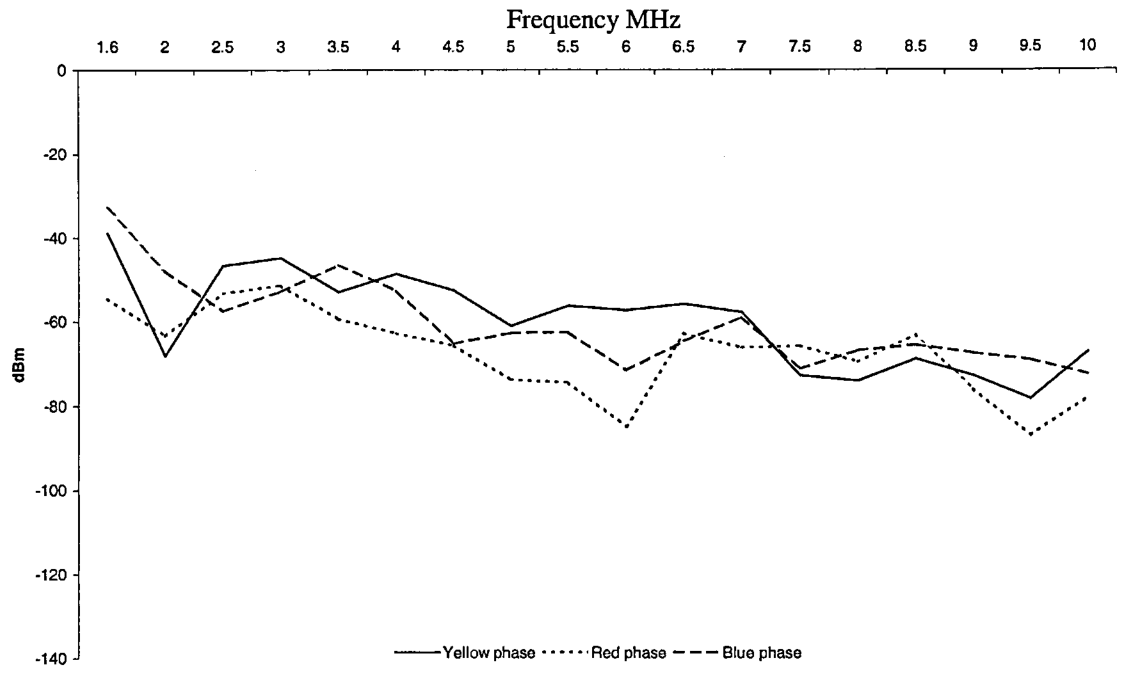


Figure 4.45: Signal attenuation between the research hut and Link Box 13 on Burneside road

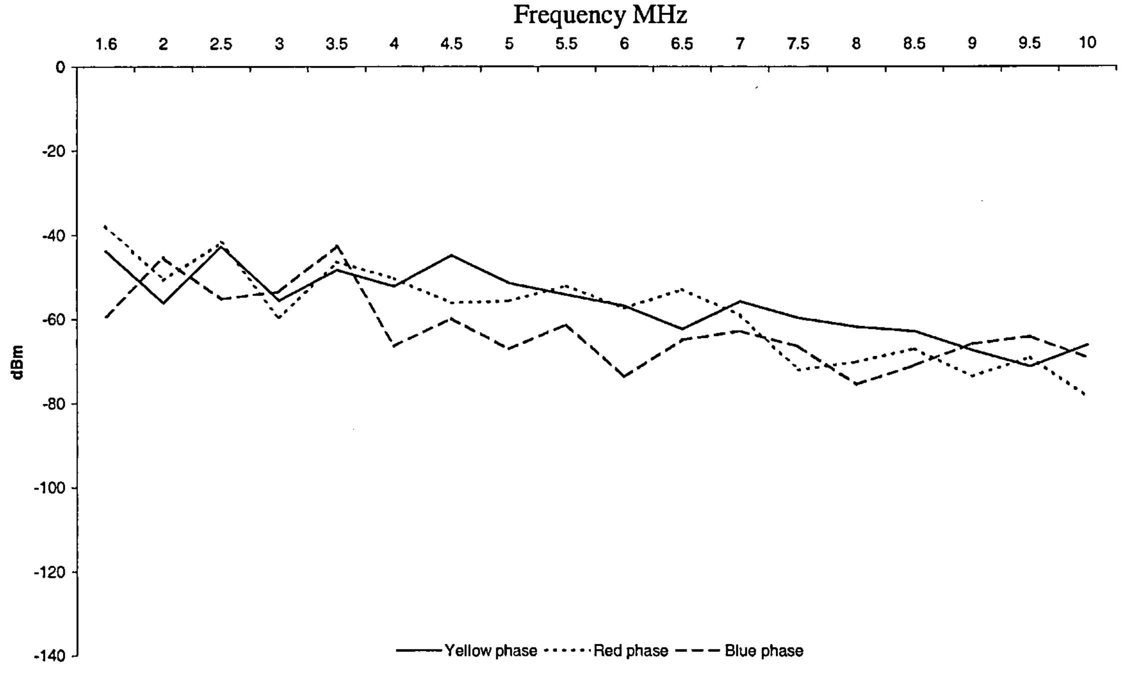


Figure 4.46: Signal attenuation between the research hut and Link Box 19 on Kentrigg road

It was stated earlier in this chapter that the attenuation characteristics at any particular location on a Low Voltage Distribution Network would remain stable so long as the network did not change. The addition of Conditioning Units to most of the houses along Applerigg represented a change to the network and therefore some small changes in the attenuation characteristics were expected. This could be confirmed by comparing the original results from 30 Applerigg with results obtained after the addition of all the Conditioning Units along Applerigg.

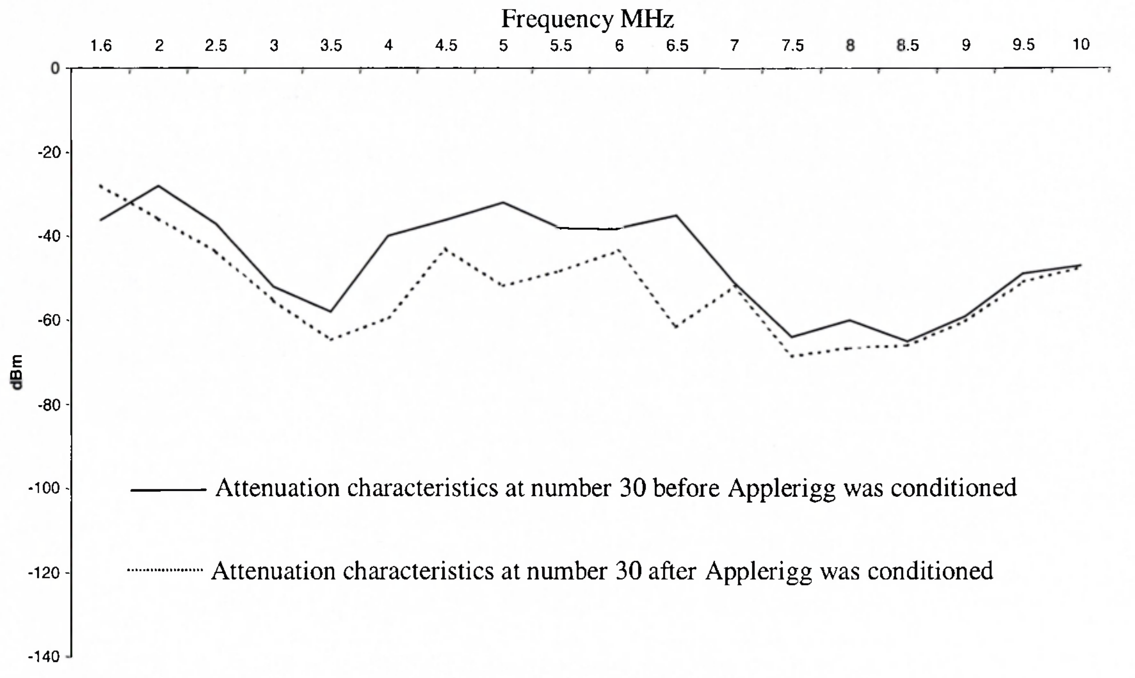


Figure 4.47: Change in attenuation characteristics due to changes in the Low Voltage Distribution Network

4.5.3 Slow speed data tests

In order to monitor the network's ability to provide a stable communications channel, over an extended period of time, an automated transmission test was devised. Using two desktop computers, and modems designed for radio packet communications, a continuous series of ASCII characters were transmitted from the research hut, to 30 Applerigg, over the Low Voltage Distribution Network. At number 30 Applerigg, the received data was checked and any errors recorded. Using a data rate of 110 baud, only 197 errors were recorded over an eight-day period, once again proving the viability of the network as a medium for communications as well as power.

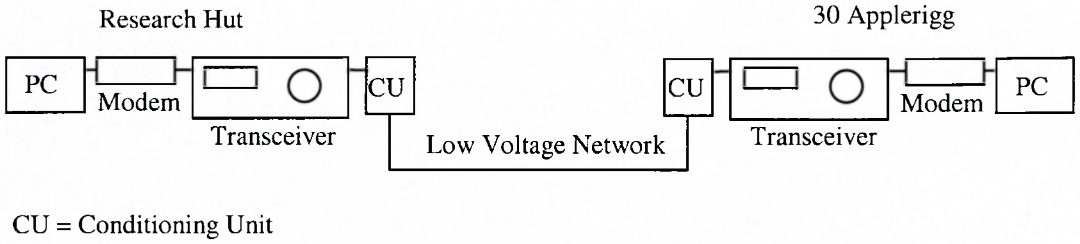


Figure 4.48: Equipment set-up for data error test

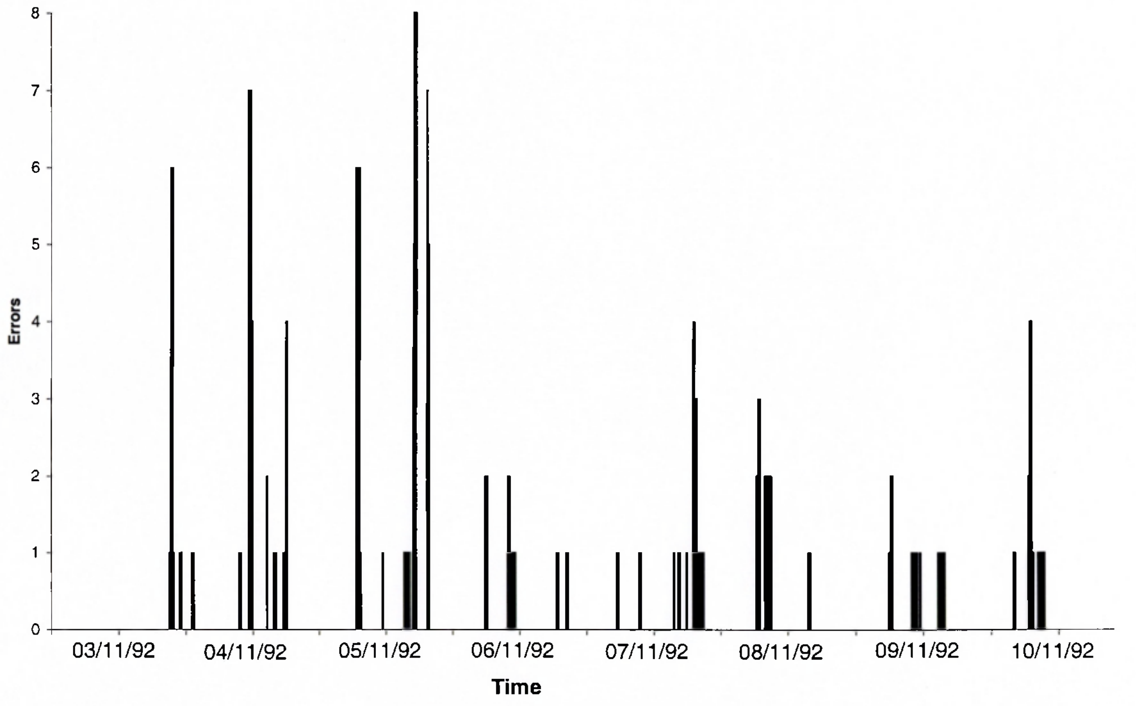


Figure 4.49: Bit errors experienced on the Low Voltage Network between the 3rd and 10th of November 1992

4.5.4 Telephony services over the Low Voltage Distribution Network

One possible use for a communications system using the Low Voltage Distribution Network is the provision of telephony services. Many developing countries have some form of power network but poorly developed telephone networks. So long as acceptable voice communication is possible over the existing power network, Power Line Communications could offer a significantly cheaper alternative to the installation of a new communications network.

As described earlier in this chapter, analogue voice tests on the Kentrigg network, using radio transceivers between the research hut and various locations around Applerigg had proved very successful. Indeed, the quality of the received signal for the relatively small transmit power was better than expected. The low level of ambient noise did not degrade the quality of the received voice and higher-powered transients did not last long enough to produce an appreciable reduction in speech quality.

After some investigation, the group became aware of a device capable of providing transparent telephony services via a full duplex radio link. The 'Model 72, Extend-A-Line' from Zetron was designed to provide a telephone link to remote sites, where the installation of a telephone network was impossible or impractical. Offshore oil and gas rigs, or remote mining operations would be typical users of this type of technology.

4.5.4.1 Mode of operation

At the user end, a standard telephone is plugged into the 'Extend-A-Line' unit, which is in turn connected to two radio transceivers, one set to transmit on frequency f_1 and the other set to receive on frequency f_2. The unit generates all the usual telephony signals such as ring, call progress, off-hook and busy tones. It also controls the operation of the two radio transceivers.

The remote 'Extend-A-Line' unit is located close to an existing telephone network. Once again the unit is connected to two transceivers, the receiving transceiver is set to frequency f_1 and the transmitting transceiver is set to frequency f_2. The remote unit is then connected to the telephone network and generates all of the required telephony signals.

Although connected to only one telephone line at the remote end, the 'Extend-A-Line' can offer a 'party line' service to the user, therefore catering for more than one telephone at the same site.

4.5.4.2 Set-up at Applerigg

A number of BT telephone lines were terminated in the research hut. The remote Zetron unit was connected to one of these lines and controlled two radio transceivers. The output from the transceivers was combined in a 'splitter unit' and connected to the Low Voltage Distribution Network via a coupling unit. At number 30 Applerigg, a standard telephone was connected to the Zetron's user unit. Once again this unit controlled two radio transceivers and was connected to the Low Voltage Distribution Network via the Conditioning Unit.

Once installed and configured, the Zetron 'Extend-A-Line' provided transparent telephony with a voice quality similar to that expected from a standard telephone network.

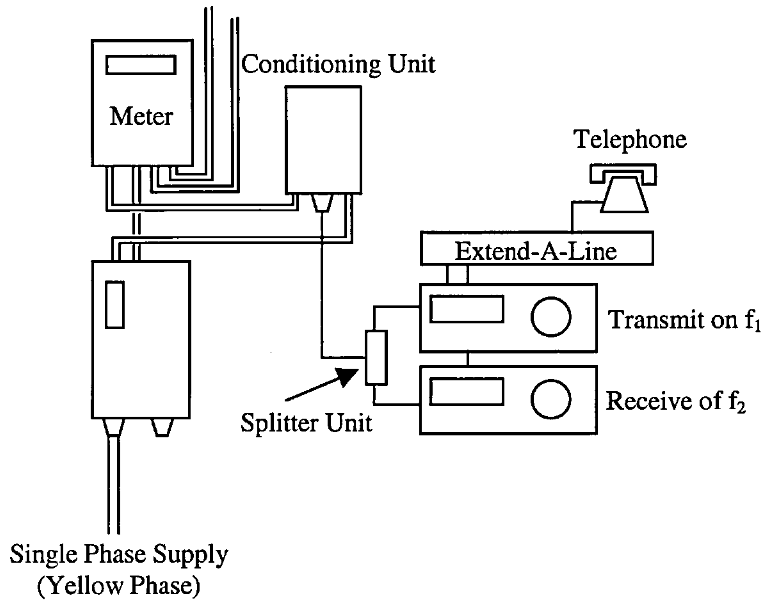


Figure 4.50: User end set-up at 30 Applerigg

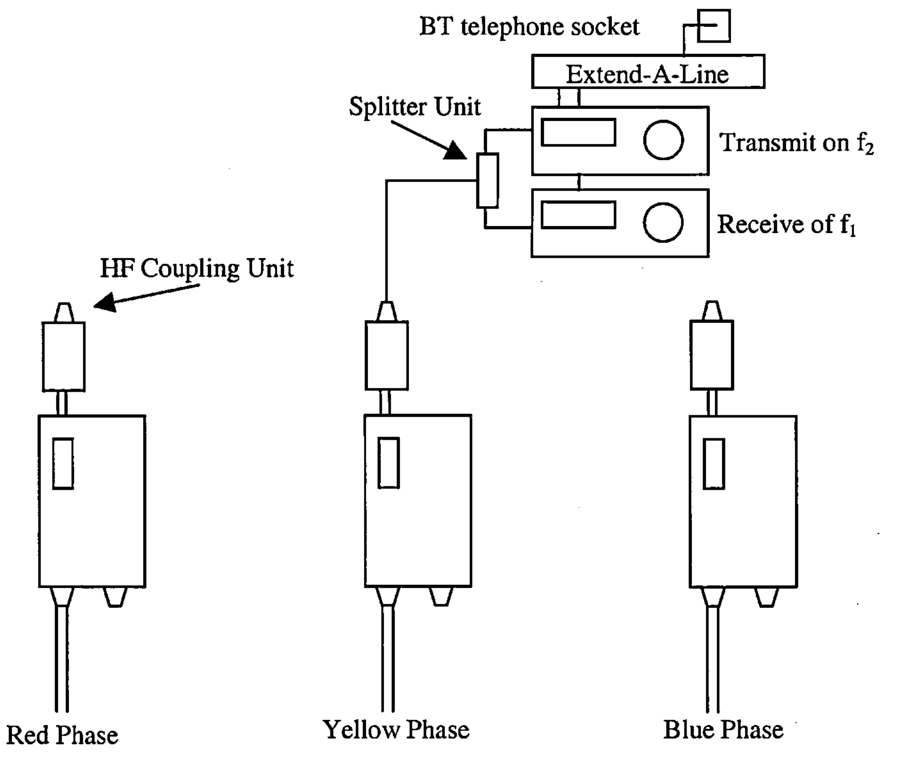


Figure 4.51: Remote end set-up in the research hut

Chapter four has described, in some detail, the research work undertaken in Kendal, Cumbria. It highlighted the limited resources available to the research group, and the solutions developed by the group in order to obtain meaningful results. It described the thinking behind the Conditioned network concept, and the design rules used to develop the Conditioning Unit. The chapter also discussed the testing philosophy that was developed in order to analyse the propagation characteristics of signals greater than 1 MHz on a typical UK Low Voltage Distribution Network. Test results were presented in order to support the argument that, although the Low Voltage Distribution Network may not present an ideal communications medium, it could offer an acceptable alternative to existing access methods such as the local loop and cable.

In Chapter five a mathematical model is derived for the Conditioning Unit and the resulting transfer function is compared with the empirical results obtained in the Applerigg field trials.

Chapter 5: Derivation of the Conditioning Unit transfer function

5.1 Introduction

Selecting frequencies above 1 MHz provides an opportunity to develop added value services on top of a Utilities desire for Remote Meter Reading, Remote Load Control and the like. Value added services could provide the incentive for the domestic market to share in the cost of rolling out a Power Line Communications system. As stated earlier, the author has reservations about the cost efficiency of rolling out a system with limited bandwidth and slow data rates, whilst existing methods of obtaining charging information for the domestic market continue to be cheap and reliable.

Conversely, the disadvantage of using frequencies above 1 MHz is that they fall well outside the frequency range set aside for Power Line Communications in the CENELEC standard, EN 50065-1. Any interference to official users of these frequencies by high frequency PLC systems would be unacceptable, and so every effort must be made to reduce PLC interference to an acceptable level. Keeping power levels to a minimum is a good starting point and, as indicated in Chapter four, injected power levels of approximately 1 mW or even lower should provide full coverage for most UK and European networks. As most European Low Voltage Distribution Networks are underground, further reductions in interference signal strength can be achieved by the inclusion of a series filter close to where service cables leave the ground. As discussed in Chapter four, developing a series low pass filter for use with communication frequencies greater than 1 MHz is significantly easier than developing a filter for frequencies within the CENELEC bands. Circuit complexity and component numbers can be kept to a minimum, resulting in a design that is relatively cheap to produce. Cost of production is critical for an element that is designed for installation at all service points on a Low Voltage Distribution Network, including locations that do not require a PLC service.

In Chapter five, the transfer function for the filter element of the Conditioning Unit, which the group designed specifically for this project, will be derived. Initially, the circuit elements are treated in the usual classical fashion, a transfer function derived and the results compared to empirical data obtained from a Conditioning Unit. This results in a point where the theoretical and observed characteristics diverge. The reasons for this divergence are discussed and a possible solution put forward. A second transfer function is then derived and again these results are compared with data obtained from the Conditioning Unit.

Simulation packages such as P-Spice can be used to determine the characteristics of electronic circuits. The results presented in this chapter were compared to a Spice model in order to confirm the accuracy of the results.

5.2 Derivation of the transfer function for a domestic CU filter section

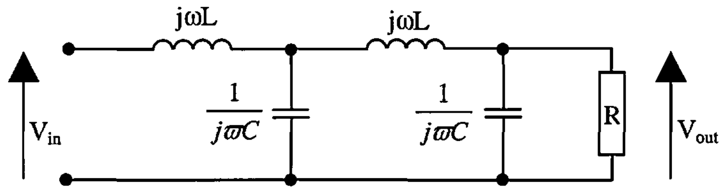


Figure 5.1: Conditioning Unit schematic

Simplifying the circuit allows the transfer function to be derived.

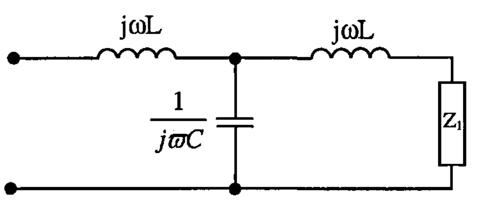


Figure 5.2: Step one, determine the value of Z_1

$$Z_1 = \frac{R \times \frac{1}{j\varpi C}}{R + \frac{1}{j\varpi C}} \qquad \textbf{(Eqn. 5.1)}$$

Multiply equation 5.1 by $\frac{j\varpi C}{j\varpi C}$

$$= \frac{R \times \frac{1}{j\varpi C}}{R + \frac{1}{j\varpi C}} \times \frac{j\varpi C}{j\varpi C}$$

$$Z_1 = \frac{R}{1 + j\varpi CR} \qquad \textbf{(Eqn. 5.2)}$$

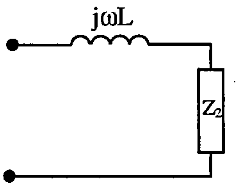


Figure 5.3: Step two, reduce the circuit further and determine the value of Z_2

$$Z_2 = \frac{\frac{1}{j\varpi C}\left[j\varpi L + \frac{R}{1+j\varpi CR}\right]}{\frac{1}{j\varpi C} + j\varpi L + \frac{R}{1+j\varpi CR}} \qquad \textbf{(Eqn. 5.3)}$$

Multiply equation 5.3 by $\frac{j\varpi C}{j\varpi C}$

$$= \frac{\frac{1}{j\varpi C}\left[j\varpi L + \frac{R}{1+j\varpi CR}\right]}{\frac{1}{j\varpi C} + j\varpi L + \frac{R}{1+j\varpi CR}} \times \frac{j\varpi C}{j\varpi C}$$

$$= \frac{\frac{j\varpi C}{j\varpi C}\left[j\varpi L + \frac{R}{1+j\varpi CR}\right]}{\frac{j\varpi C}{j\varpi C} + j\varpi L[j\varpi C] + \frac{R[j\varpi C]}{1+j\varpi CR}}$$

$$= \frac{j\varpi L + \frac{R}{1+j\varpi CR}}{1 + j^2\varpi^2 LC + \frac{j\varpi CR}{1+j\varpi CR}} \qquad \textbf{(Eqn. 5.4)}$$

Multiply equation 5.4 by $\dfrac{1+j\varpi CR}{1+j\varpi CR}$

$$=\frac{j\varpi L+\dfrac{R}{1+j\varpi CR}}{1-\varpi^2 LC+\dfrac{j\varpi CR}{1+j\varpi CR}}\times\frac{1+j\varpi CR}{1+j\varpi CR}$$

$$=\frac{j\varpi L[1+j\varpi CR]+R}{[1+j\varpi CR]-\varpi^2 LC[1+j\varpi CR]+j\varpi CR}$$

$$=\frac{j\varpi L+j^2\varpi^2 LCR+R}{1+j\varpi CR-\varpi^2 LC-j\varpi^3 LC^2 R+j\varpi CR}$$

$$=\frac{j\varpi L-\varpi^2 LCR+R}{1+j2\varpi CR-\varpi^2 LC-j\varpi^3 LC^2 R}$$

$$Z_2=\frac{R-\varpi^2 LCR+j\varpi L}{[1-\varpi^2 LC]+j\varpi CR[2-\varpi^2 LC]} \qquad \textbf{(Eqn. 5.5)}$$

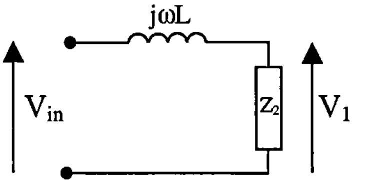


Figure 5.4: Step three, derive the transfer function using V_{in} and the intermediate voltage V_1

$$V_1=V_{in}\times\frac{Z_2}{Z_2+j\varpi L}$$

$$\frac{V_1}{V_{in}} = \frac{Z_2}{Z_2 + j\varpi L}$$

$$= \frac{\dfrac{R - \varpi^2 LCR + j\varpi L}{[1-\varpi^2 LC] + j\varpi CR[2-\varpi^2 LC]}}{\dfrac{R - \varpi^2 LCR + j\varpi L}{[1-\varpi^2 LC] + j\varpi CR[2-\varpi^2 LC]} + j\varpi L} \qquad \textbf{(Eqn. 5.6)}$$

Multiply equation 5.6 by $\dfrac{[1-\varpi^2 LC] + j\varpi CR[2-\varpi^2 LC]}{[1-\varpi^2 LC] + j\varpi CR[2-\varpi^2 LC]}$

$$= \frac{R - \varpi^2 LCR + j\varpi L}{R - \varpi^2 LCR + j\varpi L + j\varpi L[1-\varpi^2 LC + j\varpi CR[2-\varpi^2 LC]]}$$

$$= \frac{R - \varpi^2 LCR + j\varpi L}{R - \varpi^2 LCR + j\varpi L + j\varpi L - j\varpi^3 L^2 C + j^2\varpi^2 LCR[2-\varpi^2 LC]}$$

$$= \frac{R - \varpi^2 LCR + j\varpi L}{R - \varpi^2 LCR + j\varpi L + j\varpi L - j\varpi^3 L^2 C - 2\varpi^2 LCR + \varpi^4 L^2 C^2 R}$$

$$= \frac{R - \varpi^2 LCR + j\varpi L}{R - 3\varpi^2 LCR + \varpi^4 L^2 C^2 R + j2\varpi L - j\varpi^3 L^2 C}$$

$$\frac{V_1}{V_{in}} = \frac{R - \varpi^2 LCR + j\varpi L}{R + \varpi^2 LCR[-3 + \varpi^2 LC] + j\varpi L[2-\varpi^2 LC]} \qquad \textbf{(Eqn. 5.7)}$$

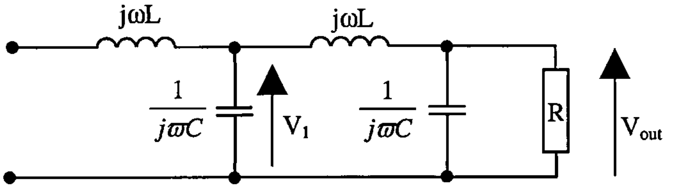


Figure 5.5: Step four, derive the transfer function using the intermediate voltage V_1 and V_{out}

$$V_{out} = V_1 \times \frac{Z_1}{Z_1 + j\varpi L}$$

$$\frac{V_{out}}{V_1} = \frac{\dfrac{R}{1 + j\varpi CR}}{\dfrac{R}{1 + j\varpi CR} + j\varpi L} \qquad \textbf{(Eqn. 5.8)}$$

Multiply equation 5.8 by $\dfrac{1 + j\varpi CR}{1 + j\varpi CR}$

$$= \frac{R}{R + j\varpi L[1 + j\varpi CR]}$$

$$= \frac{R}{R + j\varpi L + j^2\varpi^2 LCR}$$

$$= \frac{R}{R + j\varpi L - \varpi^2 LCR}$$

$$\frac{V_{out}}{V_1} = \frac{R}{R - \varpi^2 LCR + j\varpi L} \qquad \textbf{(Eqn. 5.9)}$$

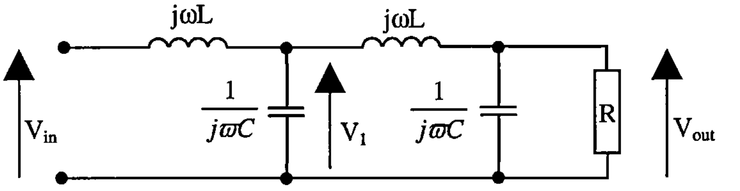


Figure 5.6: Step five, derive the transfer function using V_{in} and V_{out}

$$\frac{V_{out}}{V_{in}} = \frac{V_1}{V_{in}} \times \frac{V_{out}}{V_1}$$

$$= \frac{R - \varpi^2 LCR + j\varpi L}{R + \varpi^2 LCR[-3 + \varpi^2 LC] + j\varpi L[2 - \varpi^2 LC]} \times \frac{R}{R - \varpi^2 LCR + j\varpi L}$$

$$\frac{V_{out}}{V_{in}} = \frac{R}{R + \varpi^2 LCR[-3 + \varpi^2 LC] + j\varpi L[2 - \varpi^2 LC]}$$ **(Eqn. 5.10)**

Once the values of all the components are included in equation 5.10, a graph showing attenuation over the frequency range of interest can be generated. The Conditioning Unit was tested using a HP 8591E Spectrum Analyser and tracking generator with a Characteristic Impedance of 50 Ω. Although the Characteristic Impedances of both the Low Voltage Distribution Network and domestic wiring vary, from below 10 Ω to greater than 70 Ω, and change over time, terminating the Conditioning Unit in a 50 Ω impedance was not unrealistic.

From Chapter four:

- Each inductor has a value of approximately 18 μH.
- 22 nF, Class Y capacitors were used.

Microsoft Excel was used to generate the following plot for the frequencies up to 100 Mhz. A full listing of all the values obtained from equation 5.10 can be found in Appendix 1.

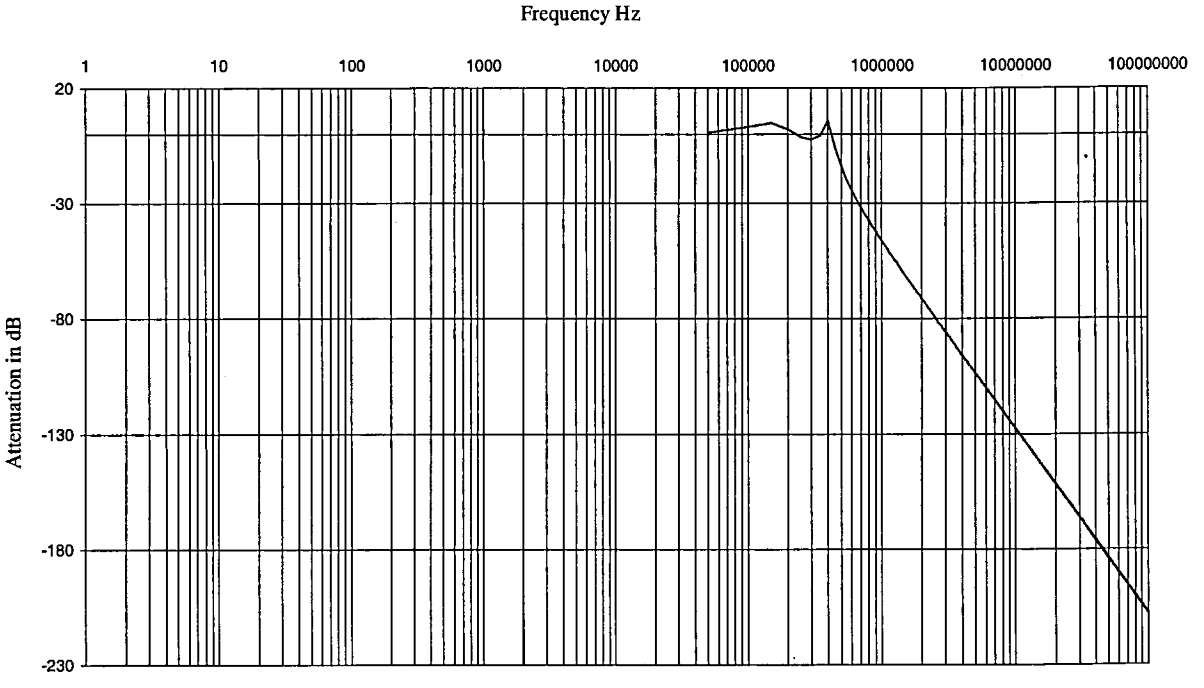


Figure 5.7: Resultant plot from equation 5.10

The following plot shows the results obtained from a Conditioning Unit tested in the laboratory in the frequency range 100 kHz to 30 MHz.

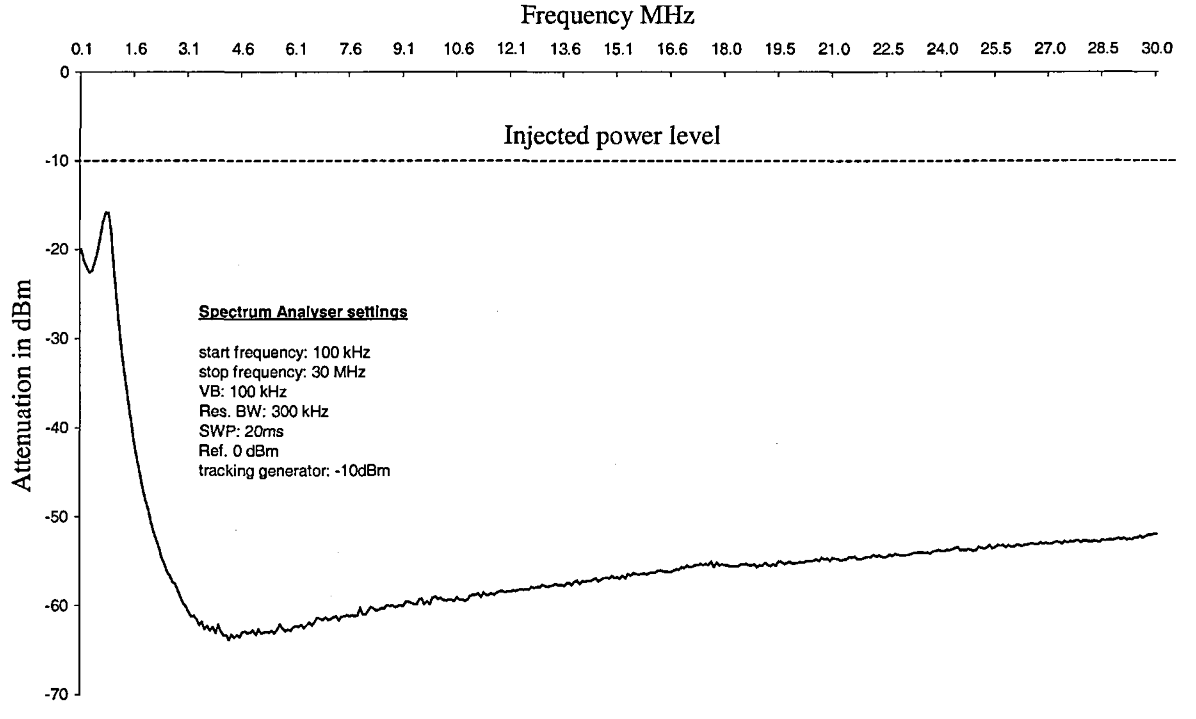


Figure 5.8: Attenuation characteristics of a Conditioning Unit in the frequency range 100 kHz to 30 MHz

Figure 5.8 shows an attenuation characteristic that reaches a maximum of approximately -64 dBm at 3.5 MHz, after which, signal attenuation levels off and then starts to fall away as frequency increases.

In figure 5.9, both the empirical and theoretical results are included for comparison. The empirical results have been corrected to take account of the injected power level.

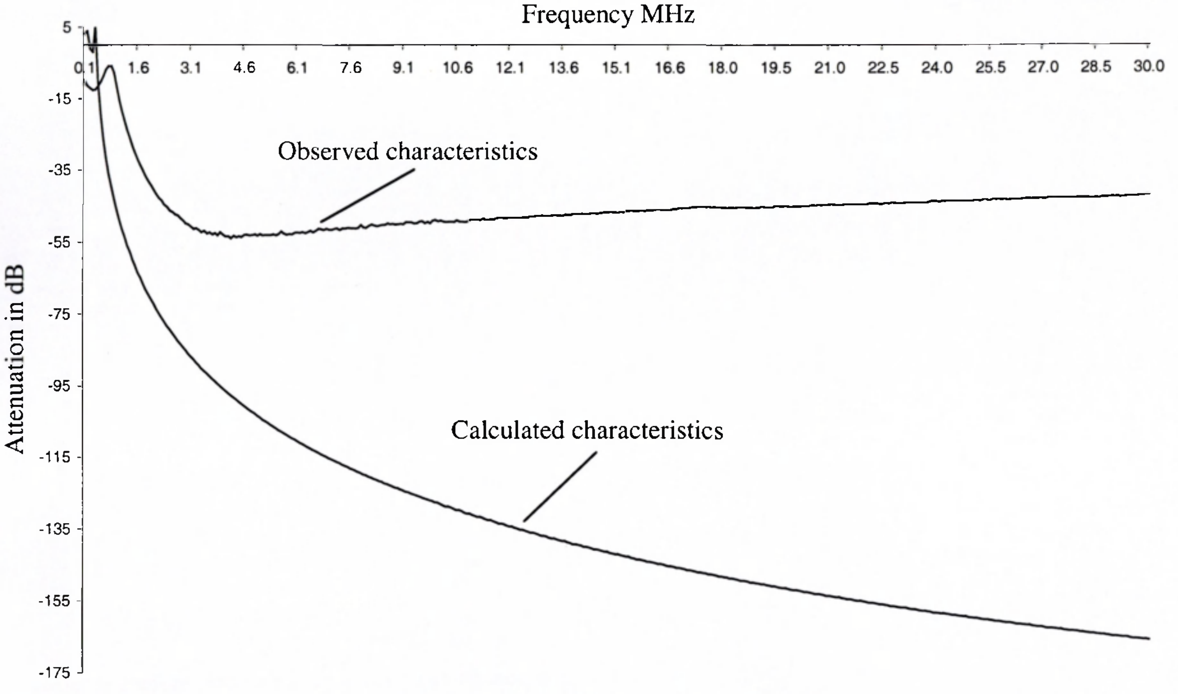


Figure 5.9: Observed and calculated attenuation characteristics for the Conditioning Unit filter section

Equation 5.10 predicts the attenuation characteristics of the circuit in figure 5.1 in isolation. What must also be taken into consideration is the physical size and construction of the Conditioning Unit. With reference to figure 4.3 in Chapter four, each inductor in the Conditioning Unit filter section is approximately 85 mm long, and was constructed from lacquered copper bar with a 12.5 mm^2 cross sectional area. The inductors have a 17 mm diameter and twenty turns, with each turn sitting tightly against its neighbours. Inevitably there will be parasitic capacitance between each of the turns in the inductor. In addition, the whole assembly was bent back on itself in order to fit into an earthed die-cast box, introducing more parasitic capacitance.

If the parasitic capacitance across each inductor turn is bundled together in order to produce a single capacitance in parallel with the inductor, the problem can be simplified and the transfer function re-evaluated.

5.3 Derivation of the transfer function for a domestic CU filter section with added parasitic capacitance

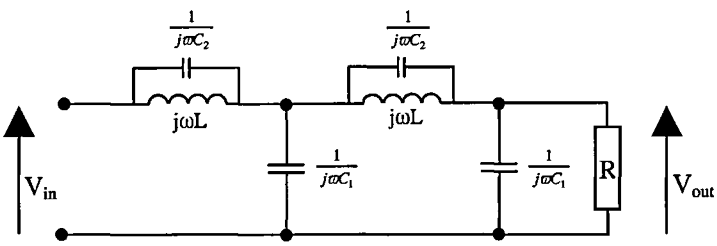


Figure 5.10: Conditioning Unit schematic

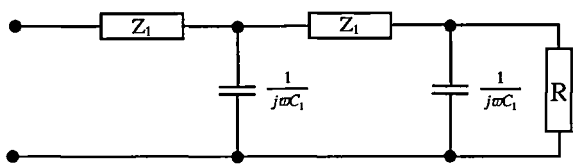


Figure 5.11: Step one, determine the value of Z_1

$$Z_1 = \frac{\frac{1}{j\varpi C_2} \times j\varpi L}{\frac{1}{j\varpi C_2} + j\varpi L} \qquad \textbf{(Eqn. 5.11)}$$

Multiply equation 5.11 by $\frac{j\varpi C_2}{j\varpi C_2}$

$$= \frac{j\varpi L}{1 + j\varpi L[j\varpi C_2]}$$

$$= \frac{j\varpi L}{1 + j^2\varpi^2 LC_2}$$

$$Z_1 = \frac{j\varpi L}{1 - \varpi^2 LC_2} \qquad \textbf{(Eqn. 5.12)}$$

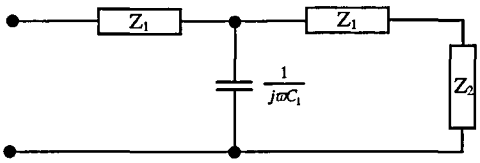


Figure 5.12: Step two, determine the value of Z_2

From Equation 5.2

$$Z_2=\frac{R}{1+j\varpi C_1 R}$$

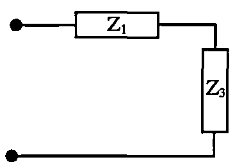


Figure 5.13: Step three, determine the value of Z_3

$$Z_3=\frac{\frac{1}{j\varpi C_1}[Z_1+Z_2]}{\frac{1}{j\varpi C_1}+Z_1+Z_2} \qquad \textbf{(Eqn. 5.13)}$$

Multiply equation 5.13 by $\frac{j\varpi C_1}{j\varpi C_1}$

$$=\frac{Z_1+Z_2}{1+Z_1[j\varpi C_1]+Z_2[j\varpi C_1]}$$

$$=\frac{\frac{j\varpi L}{1-\varpi^2 LC_2}+\frac{R}{1+j\varpi C_1 R}}{1+\frac{j\varpi L}{1-\varpi^2 LC_2}[j\varpi C_1]+\frac{R}{1+j\varpi C_1 R}[j\varpi C_1]}$$

$$=\frac{\frac{j\varpi L}{1-\varpi^2 LC_2}+\frac{R}{1+j\varpi C_1 R}}{1+\frac{j^2\varpi^2 LC_1}{1-\varpi^2 LC_2}+\frac{j\varpi C_1 R}{1+j\varpi C_1 R}}$$

$$=\frac{\dfrac{j\varpi L[1+j\varpi C_1R]+R[1-\varpi^2LC_2]}{[1-\varpi^2LC_2][1+j\varpi C_1R]}}{1+\dfrac{[j^2\varpi^2LC_1][1+j\varpi C_1R]+[j\varpi C_1R][1-\varpi^2LC_2]}{[1-\varpi^2LC_2][1+j\varpi C_1R]}} \qquad \textbf{(Eqn. 5.14)}$$

Multiply equation 5.14 by $\dfrac{[1-\varpi^2LC_2][1+j\varpi C_1R]}{[1-\varpi^2LC_2][1+j\varpi C_1R]}$

$$=\frac{j\varpi L[1+j\varpi C_1R]+R[1-\varpi^2LC_2]}{[1-\varpi^2LC_2][1+j\varpi C_1R]+[j^2\varpi^2LC_1][1+j\varpi C_1R]+j\varpi C_1R[1-\varpi^2LC_2]}$$

$$=\frac{R-\varpi^2LC_2R-\varpi^2LC_1R+j\varpi L}{1-\varpi^2LC_2-\varpi^2LC_1+j\varpi C_1R-j\varpi^3LC_1C_2R-j\varpi^3LC_1^2R+j\varpi C_1R-j\varpi^3LC_1C_2R}$$

$$=\frac{R-\varpi^2LR[C_1+C_2]+j\varpi L}{1-\varpi^2L[C_1+C_2]+j2\varpi C_1R-j2\varpi^3LC_1C_2R-j\varpi^3LC_1^2R}$$

$$Z_3=\frac{R-\varpi^2LR[C_1+C_2]+j\varpi L}{1-\varpi^2L[C_1+C_2]+j\varpi C_1R[2-2\varpi^2LC_2-\varpi^2LC_1]} \qquad \textbf{(Eqn. 5.15)}$$

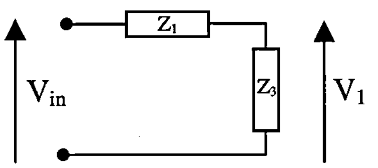


Figure 5.14: Step four: derive the transfer function using V_{in} and the intermediate voltage V_1

$$\frac{V_1}{V_{in}}=\frac{Z_3}{Z_1+Z_3}$$

$$=\frac{\dfrac{R-\varpi^2LR[C_1+C_2]+j\varpi L}{1-\varpi^2L[C_1+C_2]+j\varpi C_1R[2-2\varpi^2LC_2-\varpi^2LC_1}}{\dfrac{j\varpi L}{1-\varpi^2LC_2}+\dfrac{R-\varpi^2LR[C_1+C_2]+j\varpi L}{1-\varpi^2L[C_1+C_2]+j\varpi C_1R[2-2\varpi^2LC_2-\varpi^2LC_1]}}$$

$$=\frac{\dfrac{R-\varpi^2 LR[C_1+C_2]+j\varpi L}{1-\varpi^2 L[C_1+C_2]+j\varpi C_1 R[2-2\varpi^2 LC_2-\varpi^2 LC_1]}}{\dfrac{j\varpi L[1-\varpi^2 L[C_1+C_2]+j\varpi C_1 R[2-2\varpi^2 LC_2-\varpi^2 LC_1]]+[1-\varpi^2 LC_2][R-\varpi^2 LR[C_1+C_2]+j\varpi L]}{[1-\varpi^2 LC_2][1-\varpi^2 L[C_1+C_2]+j\varpi C_1 R[2-2\varpi^2 LC_2-\varpi^2 LC_1]]}}$$

$$=\frac{R-\varpi^2 LR[C_1+C_2]+j\varpi L}{\dfrac{j\varpi L[1-\varpi^2 L[C_1+C_2]+jwC_1 R[2-2\varpi^2 LC_2-\varpi^2 LC_1]]+[1-\varpi^2 LC_2][R-\varpi^2 LR[C_1+C_2]+j\varpi L]}{1-\varpi^2 LC_2}}$$

$$=\frac{[1-\varpi^2 LC_2][R-\varpi^2 LR[C_1+C_2]+j\varpi L]}{j\varpi L[1-\varpi^2 L[C_1+C_2]+j\varpi C_1 R[2-2\varpi^2 LC_2-\varpi^2 LC_1]]+[1-\varpi^2 LC_2][R-\varpi^2 LR[C_1+C_2]+j\varpi L]}$$

(Eqn. 5.16)

Looking at the numerator of equation 5.16

Numerator = $[1-\varpi^2 LC_2][R-\varpi^2 LR[C_1+C_2]+j\varpi L]$

$$=R-\varpi^2 LC_1 R-\varpi^2 LC_2 R+j\varpi L-\varpi^2 LC_2 R+\varpi^4 L^2 C_1 C_2 R+\varpi^4 L^2 C_2^2 R-j\varpi^3 L^2 C_2$$

$$=R-\varpi^2 LC_1 R-2\varpi^2 LC_2 R+\varpi^4 L^2 C_1 C_2 R+\varpi^4 L^2 C_2^2 R+j\varpi L-j\varpi^3 L^2 C_2$$

$$=R-\varpi^2 LR[C_1+2C_2-\varpi^2 LC_1 C_2-\varpi^2 LC_2^2]+j\varpi L[1-\varpi^2 LC_2]$$

Numerator $=R-\varpi^2 LR[C_1+2C_2-\varpi^2 LC_2[C_1+C_2]]+j\varpi L[1-\varpi^2 LC_2]$

Looking at the denominator of equation 5.16

$$\text{Denominator} = j\varpi L[1-\varpi^2 L[C_1+C_2]+j\varpi C_1 R[2-2\varpi^2 LC_2-\varpi^2 LC_1]] + [1-\varpi^2 LC_2][R-\varpi^2 LR[C_1+C_2]+j\varpi L]$$

$$= j\varpi L - j\varpi^3 L^2 C_1 - j\varpi^3 L^2 C_2 - 2\varpi^2 LC_1 R + 2\varpi^4 L^2 C_1 C_2 R + \varpi^4 L^2 C_1^2 R + R - \varpi^2 LC_1 R - 2\varpi^2 LC_2 R + \varpi^4 L^2 C_1 C_2 R + \varpi^4 L^2 C_2^2 R + j\varpi L - j\varpi^3 L^2 C_2$$

$$= R - 3\varpi^2 LC_1 R - 2\varpi^2 LC_2 R + 3\varpi^4 L^2 C_1 C_2 R + \varpi^4 L^2 C_1^2 R + \varpi^4 L^2 C_2^2 R + j2\varpi L - j\varpi^3 L^2 C_1 - j2\varpi^3 L^2 C_2$$

$$\text{Denominator} = R - \varpi^2 LR[3C_1 + 2C_2 - \varpi^2 L[C_1^2 + C_2^2] - 3\varpi^2 LC_1 C_2] + j\varpi L[2 - \varpi^2 LC_1 - 2\varpi^2 LC_2]$$

$$\frac{V_1}{V_{in}} = \frac{R - \varpi^2 LR[C_1 + 2C_2 - \varpi^2 LC_2[C_1 + C_2]] + j\varpi L[1 - \varpi^2 LC_2]}{R - \varpi^2 LR[3C_1 + 2C_2 - \varpi^2 L[C_1^2 + C_2^2] - 3\varpi^2 LC_1 C_2] + j\varpi L[2 - \varpi^2 LC_1 - 2\varpi^2 LC_2]} \quad \textbf{(Eqn. 5.17)}$$

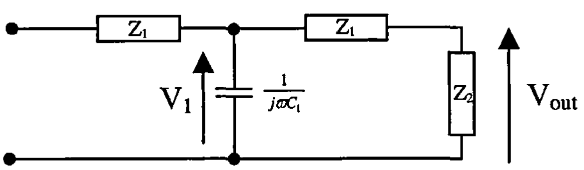


Figure 5.15: Step five, derive the transfer function using the intermediate voltage V_1 and V_{out}

$$\frac{V_{out}}{V_1} = \frac{Z_2}{Z_1 + Z_2}$$

$$= \frac{\dfrac{R}{1 + j\varpi C_1 R}}{\dfrac{j\varpi L}{1 - \varpi^2 LC_2} + \dfrac{R}{1 + j\varpi C_1 R}}$$

$$= \frac{\dfrac{R}{1 + j\varpi C_1 R}}{\dfrac{j\varpi L[1 + j\varpi C_1 R] + R[1 - \varpi^2 LC_2]}{[1 - \varpi^2 LC_2][1 + j\varpi C_1 R]}} \quad \textbf{(Eqn. 5.18)}$$

Multiply equation 5.18 by $\dfrac{1+j\varpi C_1 R}{1+j\varpi C_1 R}$

$$=\frac{R}{\dfrac{j\varpi L[1+j\varpi C_1 R]+R[1-\varpi^2 LC_2]}{[1-\varpi^2 LC_2]}}$$

$$=\frac{R[1-\varpi^2 LC_2]}{j\varpi L[1+j\varpi C_1 R]+R[1-\varpi^2 LC_2]}$$

$$=\frac{R[1-\varpi^2 LC_2]}{j\varpi L+j^2\varpi^2 LC_1 R+R[1-\varpi^2 LC_2]}$$

$$=\frac{R[1-\varpi^2 LC_2]}{R[1-\varpi^2 LC_2]-\varpi^2 LC_1 R+j\varpi L}$$

$$\frac{V_{out}}{V_1}=\frac{R[1-\varpi^2 LC_2]}{R-\varpi^2 LR[C_1+C_2]+j\varpi L} \qquad \textbf{(Eqn. 5.19)}$$

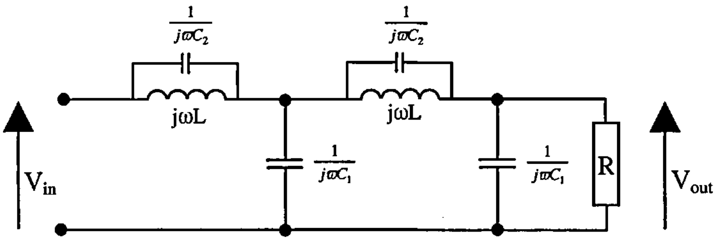


Figure 5.16: Step six: derive the transfer function using V_{in} and V_{out}

$$\frac{V_{out}}{V_{in}}=\frac{V_1}{V_{in}}\times\frac{V_{out}}{V_1}$$

$$=\frac{R-\varpi^2 LR[C_1+2C_2-\varpi^2 LC_2[C_1+C_2]]+j\varpi L[1-\varpi^2 LC_2]}{R-\varpi^2 LR[3C_1+2C_2-\varpi^2 L[C_1^2+C_2^2]-3\varpi^2 LC_1C_2]+j\varpi L[2-\varpi^2 LC_1-2\varpi^2 LC_2]}$$

$$\times\frac{R[1-\varpi^2 LC_2]}{R-\varpi^2 LR[C_1+C_2]+j\varpi L} \qquad \textbf{(Eqn. 5.20)}$$

Looking at the numerator of equation 5.20

$$\text{Numerator} = [R - \varpi^2 LR[C_1 + 2C_2 - \varpi^2 LC_2[C_1 + C_2]] + j\varpi L[1 - \varpi^2 LC_2]] \times R[1 - \varpi^2 LC_2]$$

$$= [R - \varpi^2 LC_1 R - 2\varpi^2 LC_2 R + \varpi^4 L^2 C_1 C_2 R + \varpi^4 L^2 C_2^2 R + j\varpi L - j\varpi^3 L^2 C_2] \times [R - \varpi^2 LC_2 R]$$

$$= R^2 - \varpi^2 LC_1 R^2 - 3\varpi^2 LC_2 R^2 + 2\varpi^4 L^2 C_1 C_2 R^2 + 3\varpi^4 L^2 C_2^2 R^2 - \varpi^6 L^3 C_1 C_2^2 R^2 - \varpi^6 L^3 C_2^3 R^2$$
$$+ j\varpi LR - j2\varpi^3 L^2 C_2 R + j\varpi^5 L^3 C_2^2 R$$

$$\text{Numerator} = R^2 - \varpi^2 LR^2 [C_1 + 3C_2 - 2\varpi^2 LC_1 C_2 - 3\varpi^2 LC_2^2 + \varpi^4 L^2 C_1 C_2^2 + \varpi^4 L^2 C_2^3]$$
$$+ j\varpi LR[1 - 2\varpi^2 LC_2 + \varpi^4 L^2 C_2^2]$$

Looking at the denominator of equation 5.20

$$\text{Denominator} = [R - \varpi^2 LR[3C_1 + 2C_2 - \varpi^2 L[C_1^2 + C_2^2] - 3\varpi^2 LC_1 C_2] + j\varpi L[2 - \varpi^2 LC_1 - 2\varpi^2 LC_2]]$$
$$\times [R - \varpi^2 LR[C_1 + C_2] + j\varpi L]$$

$$= [R - 3\varpi^2 LC_1 R - 2\varpi^2 LC_2 R + \varpi^4 L^2 C_1^2 R + \varpi^4 L^2 C_2^2 R + 3\varpi^4 L^2 C_1 C_2 R + j2\varpi L - j\varpi^3 L^2 C_1 - j2\varpi^3 L^2 C_2]$$
$$\times [R - \varpi^2 LC_1 R - \varpi^2 LC_2 R + j\varpi L]$$

$$= -2\varpi^2 L^2 - 4\varpi^2 LC_1 R^2 - 3\varpi^2 LC_2 R^2 + \varpi^4 L^3 C_1 + 2\varpi^4 L^3 C_2 + 4\varpi^4 L^2 C_1^2 R^2 + 3\varpi^4 L^2 C_2^2 R^2$$
$$+ 8\varpi^4 L^2 C_1 C_2 R^2 - \varpi^6 L^3 C_1^3 R^2 - \varpi^6 L^3 C_2^3 R^2 - 4\varpi^6 L^3 C_1^2 C_2 R^2 - 4\varpi^6 L^3 C_1 C_2^2 R^2$$
$$+ j3\varpi LR - j6\varpi^3 L^2 C_1 R - j6\varpi^3 L^2 C_2 R + j2\varpi^5 L^3 C_1^2 R + j3\varpi^5 L^3 C_2^2 R + j6\varpi^5 L^3 C_1 C_2 R$$

$$\text{Denominator} = R^2 - \varpi^2 L[2L + 4C_1 R^2 + 3C_2 R^2] + \varpi^4 L^2 [LC_1 + 2LC_2 + 4C_1^2 R^2 + 3C_2^2 R^2 + 8C_1 C_2 R^2]$$
$$- \varpi^6 L^3 R^2 [C_1^3 + C_2^3 + 4C_1^2 C_2 + 4C_1 C_2^2]$$
$$+ j3\varpi LR - j\varpi^3 L^2 R[6C_1 + 6C_2] + j\varpi^5 L^3 R[2C_1^2 + 3C_2^2 + 6C_1 C_2]$$

$$\frac{V_{out}}{V_{in}} = \frac{R^2 - \varpi^2 LR^2 [C_1 + 3C_2 - 2\varpi^2 LC_1 C_2 - 3\varpi^2 LC_2^2 + \varpi^4 L^2 C_1 C_2^2 + \varpi^4 L^2 C_2^3] + j\varpi LR[1 - 2\varpi^2 LC_2 + \varpi^4 L^2 C_2^2]}{R^2 - \varpi^2 L[2L + 4C_1 R^2 + 3C_2 R^2] + \varpi^4 L^2 [LC_1 + 2LC_2 + 4C_1^2 R^2 + 3C_2^2 R^2 + 8C_1 C_2 R^2] - \varpi^6 L^3 R^2 [C_1^3 + C_2^3 + 4C_1^2 C_2 + 4C_1 C_2^2] + j3\varpi LR - j\varpi^3 L^2 R[6C_1 + 6C_2] + j\varpi^5 L^3 R[2C_1^2 + 3C_2^2 + 6C_1 C}$$

(Eqn. 5.21)

Using equation 5.21 and Microsoft Excel, the transfer function can be plotted. A full listing of all the values obtained from equation 5.21 can be found in Appendix 2. Once again, the component values remain the same, but this time a parasitic capacitance of 1.1 nF is included.

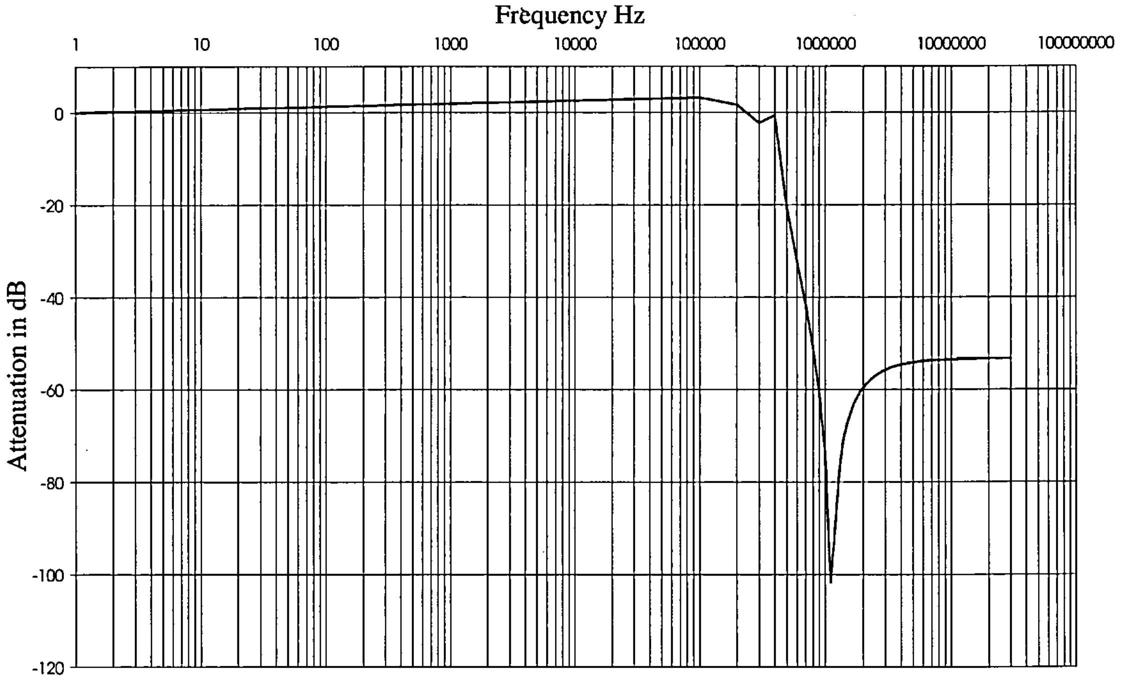


Figure 5.17: Resultant plot from equation 5.21 in the frequency range 1 Hz to 30 MHz

The inclusion of the parasitic capacitance associated with the inductors has resulted in a levelling-off of the attenuation characteristic above 2 MHz this follows the empirical results obtained in the laboratory much more closely, as can be seen in figure 5.18.

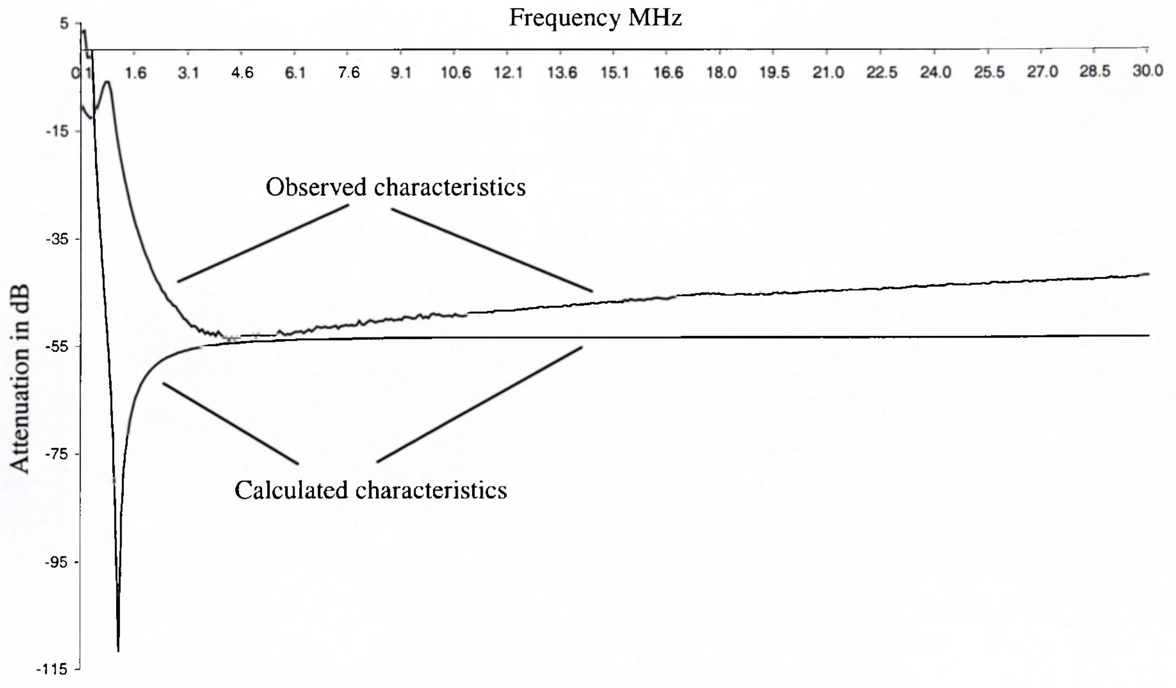


Figure 5.18: Observed and calculated attenuation characteristics for the Conditioning Unit filter section

Although the theoretical results show a much closer relationship to the empirical results, the empirical results do not contain the resonant spike at 1 MHz, and attenuation does not roll-off as quickly above 3 MHz. These differences can be accounted for as follows:

1. In order to produce a manageable transfer function, the individual parasitic capacitance across each turn of the inductor has been bundled into one parallel capacitance across the whole inductor, hence reducing accuracy.

2. As stated earlier in this chapter, the inductor assembly is contained within an earthed die-cast box. Each inductor is approximately 87 mm in length and, at their closest, no more than 5 mm away from the earthed box. Each turn of the inductor will contain its own parasitic capacitance. This capacitance, leading directly to earth, will have an increasing effect as the frequency increases, reducing the efficiency of the filter.

3. As frequencies increase, the resistance of the conductor also increases as the effective cross-sectional area is reduced due to the skin effect. This is caused by the changing magnetic flux associated with the HF signal, which increases the self-inductance of the conductor, particularly in the centre, and forces the signal to flow along the outer surface.

4. The series inductors were wound round ferrite cores, which would saturate in synchronisation with the 50 Hz power signal, reducing their efficiency.

5. The filter was housed in an earthed, die-cast box. With the large series inductors inside, the assembly can be seen as a single turn transformer leading to mutual inductive effects.

6. The proximity and size of the filter components, including the HRC fuses, will also lead to capacitive and mutual inductive effects.

Chapter 6: Conclusions and Further Work

6.1 Conclusions

This thesis describes the work undertaken by the author to investigate the use of the UK's Low Voltage Distribution Network for the purpose of communications, both voice and data. It details the development of Power Line Communications from the early 1920s, with the development of Ripple Control, through to the present day and the use of modern transmission techniques such as Spread Spectrum. Typical underground distribution networks have been discussed, including examples of some of those found in other European countries. The author believes all variations of underground network need to be included in any development work in order to produce solutions with the widest possible application. Some of the problems associated with using the Low Voltage Distribution Network for high frequency signalling have been highlighted; these include attenuation, noise, both ingress and egress, as well as position-dependant problems caused by standing waves. A detailed account of the research work undertaken in Kendal, Cumbria, has been given. The research section of this thesis describes how, with limited resources, techniques were developed in order to fully describe the high frequency transmission characteristics of the Kentrigg distribution network. The reasoning behind the decision to use frequencies greater than 1 MHz, rather than utilising those already reserved for Power Line Carrier as set out in CENELEC EN 50065-1, was outlined. The Conditioned Network concept was discussed and the development, construction and installation of the Conditioning Unit outlined. Finally, a transfer function for the filter section of the Conditioning Unit was developed and the theoretical results compared with empirical results obtained in the laboratory.

Throughout this thesis the author has emphasised his belief that commercial consideration must form an integral part of any Power Line Communication development programme. Whilst the costs associated with researching a particular technology may fall within the realms of acceptable expenditure for both academic and industrial bodies, the cost of installing and maintaining a new PLC system across a Utility's network is considerable. For any company to show this level of support for a new product, an acceptable return on their investment, in a reasonable period of time, must be demonstrated. To date this has not been done. A handful of networks servicing a few hundred customers does not constitute a commercial roll-out when a typical Utility supplies hundreds of thousands, or even millions, of domestic customers. Both the low frequency CENELEC bands, and the proposed high frequency, 1 to 30 MHz, bands still have problems to overcome.

The frequencies between 3 kHz and 148.5 kHz are already reserved for Power Line Communications and as such are supported by international agreement. The CENELEC EN 50065 series, when fully ratified, will define all the requirements for the use of these frequencies. However, the available frequency bands are narrow; the range 3 to 148.5 kHz contains five bands with bandwidths of 6 kHz, 86 kHz, 30 kHz, 15 kHz and 8.5 kHz. These available bandwidths can only provide limited data rates and hence limited but costly services. Take for example meter reading in the domestic market, and let us assume the availability of a domestic electricity meter using Power Line Carrier technology. If an electricity utility wished to convert to remote meter reading using PLC, they would first have to buy and install the required back-haul and infrastructure, probably to every substation in their network. All existing electricity meters would then have to be replaced with intelligent PLC meters. The cost of this reorganisation would be phenomenal and any long-term savings debatable for the following reasons.

1. The conventional electromechanical Ferraris disc electricity meter is accurate, cheap, requires little or no maintenance and has a life expectancy in excess of forty years.

2. Any electronic meter containing active elements will be under constant electrical stress. It is unlikely that these components could offer the same life expectancy as the Ferraris disc meter.

3. Even if the cost of manufacturing a PLC meter were similar to that of a conventional meter, the rate at which they required replacing may make them significantly more expensive in the long run.

For frequencies greater than 1 MHz, the network requirements and installation costs would be no cheaper, but this time there would be enough bandwidth to offer a number of 'value added' services (voice and/or broadband data) in addition to the more mundane Utility requirements such as remote meter reading. This would allow the Utility to share the costs with customers who wish to benefit from the services on offer. The problem here is the use of frequencies outside the band set aside for PLC and the possible problems this will cause the rightful users of those frequencies. If HF PLC is to succeed, agreement within the international standard organisations is required. At the time of writing the debate continues but the outcome is far from clear.

The issues raised above for both low and high frequency Power Line Communication may sound almost pessimistic, but that was not the intention. The author has spent much of the intervening period, between 1994 and the time this thesis was submitted, involved in the PLC industry and has shared in its high and low points. He remains positive about the future for PLC but realistic about the problems still to be resolved.

The research work carried out in Kendal, Cumbria, confirmed the belief that a typical UK Low Voltage Distribution Network is capable of supporting high frequency (greater than 1 MHz) voice and data communication. Although an underground power distribution network is far from an ideal HF transmission medium, by understanding its limitations, solutions can be developed to provide a communication channel that offers enough bandwidth to be commercially viable.

By using the underground Low Voltage Distribution Network as the medium for carrying HF signals and including the Conditioned Network concept, this research has postulated that unintentional HF interference can be kept to a minimum. Further developments in modulation and transmission techniques could reduce this interference further.

6.2 Further Work

High frequency PLC continues to offer an interesting alternative to other broadband access solutions such as ADSL, and further research is required to realise its potential.

Understanding the level, and effects, of HF PLC interference in the urban environment requires further investigation and the development of new and novel methods of testing and modelling. Many traditional methods for detecting HF interference require the use of a controlled environment. This is impossible to achieve in an urban setting where a multitude of local and long distance transmitters, power cables, telephone lines and household wiring all combine to form a matrix of networks which inevitably affect any observed results. Regulatory approval is key to the success of HF PLC, and interference from HF PLC systems remains one of the most contentious areas of debate.

The remit of this project did not extend to an investigation into the most suitable modulation and transmission techniques for HF PLC. Further work is required in order to determine optimum techniques, achieving the maximum coverage in the presence of unpredictable noise, whilst at the same time limiting the required transmit power to an acceptable level.

The low voltage substation forms a natural hub for most PLC systems. In order to inject and recover signals from the Low Voltage Distribution Network a number of connection devices will be required. These connection devices must allow high frequency signals to pass too and from the network, whilst blocking the power signal and preventing damage to transmission equipment. This is an area of work that requires a detailed understanding and appreciation of the requirements of both the PLC developers and the operators of the power network. On the one hand, these devices must be installed in such a manner as to facilitate the best communications path for high frequency signals. On the other, they must in no way interfere with the normal, safe operation of the electricity distribution network.

Appendix 1: Results from equation 5.10

The following table presents the results used to generate figure 5.7.

Frequency Hz	Attenuation dB
0	0
50000	0.80331538
100000	3.1657298
150000	4.98345782
200000	2.06258274
250000	-1.10008828
300000	-2.31183385
350000	-0.66676736
400000	5.73620983
450000	-5.72067236
500000	-14.0419619
550000	-19.8113313
600000	-24.3710329
650000	-28.2052866
700000	-31.5449921
750000	-34.5203417
800000	-37.2130962
850000	-39.6785663
900000	-41.9562491
950000	-44.075529
1000000	-46.0589767
1050000	-47.9243797
1100000	-49.6860526
1150000	-51.3557182
1200000	-52.9431194
1250000	-54.4564564
1300000	-55.9027068
1350000	-57.2878654
1400000	-58.6171257
1450000	-59.8950212
1500000	-61.1255356
1550000	-62.3121912
1600000	-63.458119
1650000	-64.566116
1700000	-65.6386926
1750000	-66.6781112
1800000	-67.6864184
1850000	-68.6654724
1900000	-69.6169659
1950000	-70.5424454
2000000	-71.4433282
2050000	-72.3209162
2100000	-73.176409
2150000	-74.0109138
2200000	-74.8254552
2250000	-75.6209833
2300000	-76.3983809
2350000	-77.1584696
2400000	-77.9020157
2450000	-78.6297349
2500000	-79.3422968
2550000	-80.0403288
2600000	-80.7244196
2650000	-81.3951224
2700000	-82.0529578
2750000	-82.6984161
2800000	-83.3319599
2850000	-83.9540261
2900000	-84.5650277
2950000	-85.1653555
3000000	-85.7553798
3050000	-86.3354518
3100000	-86.9059048
3150000	-87.4670557
3200000	-88.0192056
3250000	-88.5626412
3300000	-89.0976356
3350000	-89.6244492
3400000	-90.1433303
3450000	-90.6545162
3500000	-91.1582334
3550000	-91.6546987
3600000	-92.1441193
3650000	-92.6266937
3700000	-93.1026121
3750000	-93.5720569
3800000	-94.0352028
3850000	-94.4922177
3900000	-94.9432628
3950000	-95.3884929
4000000	-95.828057
4050000	-96.2620982
4100000	-96.6907543
4150000	-97.1141581
4200000	-97.5324373
4250000	-97.9457152
4300000	-98.3541104
4350000	-98.7577377
4400000	-99.1567076
4450000	-99.5511268
4500000	-99.9410984
4550000	-100.326722
4600000	-100.708094
4650000	-101.085308
4700000	-101.458453
4750000	-101.827616
4800000	-102.192883
4850000	-102.554335
4900000	-102.912051
4950000	-103.266108
5000000	-103.61658
5050000	-103.963539
5100000	-104.307055
5150000	-104.647196
5200000	-104.984029
5250000	-105.317616
5300000	-105.648021
5350000	-105.975303
5400000	-106.299521
5450000	-106.620733
5500000	-106.938992
5550000	-107.254355
5600000	-107.566872
5650000	-107.876595
5700000	-108.183574
5750000	-108.487857
5800000	-108.78949
5850000	-109.088521
5900000	-109.384993
5950000	-109.67895

Frequency Hz		Attenuation dB
8300000		-121.265545
8350000		-121.474489
8400000		-121.682183
8450000		-121.888641
8500000		-122.093878
8550000		-122.297908
8600000		-122.500745
8650000		-122.702404
8700000		-122.902897
8750000		-123.102239
8800000		-123.300442
8850000		-123.49752
8900000		-123.693484
8950000		-123.888349
9000000		-124.082125
9050000		-124.274825
9100000		-124.466462
9150000		-124.657046
9200000		-124.846589
9250000		-125.035102
9300000		-125.222597
9350000		-125.409085
9400000		-125.594576
9450000		-125.779081
9500000		-125.96261
9550000		-126.145174
9600000		-126.326783
9650000		-126.507446
9700000		-126.687174
9750000		-126.865976
9800000		-127.043862
9850000		-127.220841
9900000		-127.396922
9950000		-127.572114
10000000		-127.746427
10050000		-127.919868
10100000		-128.092448
10150000		-128.264173
10200000		-128.435053
10250000		-128.605096
10300000		-128.774311
10350000		-128.942704
10400000		-129.110284
10450000		-129.27706
10500000		-129.443038
10550000		-129.608226

Frequency Hz		Attenuation dB
10600000		-129.772632
10650000		-129.936263
10700000		-130.099126
10750000		-130.261229
10800000		-130.422578
10850000		-130.583181
10900000		-130.743045
10950000		-130.902176
11000000		-131.06058
11050000		-131.218265
11100000		-131.375238
11150000		-131.531503
11200000		-131.687069
11250000		-131.84194
11300000		-131.996124
11350000		-132.149626
11400000		-132.302452
11450000		-132.454609
11500000		-132.606102
11550000		-132.756936
11600000		-132.907118
11650000		-133.056654
11700000		-133.205548
11750000		-133.353806
11800000		-133.501434
11850000		-133.648437
11900000		-133.79482
11950000		-133.940588
12000000		-134.085748
12050000		-134.230302
12100000		-134.374258
12150000		-134.517619
12200000		-134.660391
12250000		-134.802578
12300000		-134.944185
12350000		-135.085217
12400000		-135.225678
12450000		-135.365574
12500000		-135.504908
12550000		-135.643685
12600000		-135.78191
12650000		-135.919587
12700000		-136.05672
12750000		-136.193313
12800000		-136.329372
12850000		-136.464899

Frequency Hz		Attenuation dB
12900000		-136.5999
12950000		-136.734377
13000000		-136.868336
13050000		-137.001781
13100000		-137.134714
13150000		-137.26714
13200000		-137.399063
13250000		-137.530487
13300000		-137.661416
13350000		-137.791852
13400000		-137.921801
13450000		-138.051265
13500000		-138.180248
13550000		-138.308754
13600000		-138.436786
13650000		-138.564348
13700000		-138.691443
13750000		-138.818074
13800000		-138.944246
13850000		-139.06996
13900000		-139.195222
13950000		-139.320033
14000000		-139.444397
14050000		-139.568317
14100000		-139.691797
14150000		-139.814839
14200000		-139.937446
14250000		-140.059623
14300000		-140.181371
14350000		-140.302694
14400000		-140.423594
14450000		-140.544075
14500000		-140.664139
14550000		-140.78379
14600000		-140.90303
14650000		-141.021862
14700000		-141.140289
14750000		-141.258313
14800000		-141.375937
14850000		-141.493165
14900000		-141.609998
14950000		-141.726439
15000000		-141.842492
15050000		-141.958157
15100000		-142.073439
15150000		-142.188339

Frequency Hz	Attenuation dB
15200000	-142.302861
15250000	-142.417006
15300000	-142.530777
15350000	-142.644177
15400000	-142.757208
15450000	-142.869872
15500000	-142.982171
15550000	-143.094109
15600000	-143.205687
15650000	-143.316908
15700000	-143.427774
15750000	-143.538287
15800000	-143.648449
15850000	-143.758264
15900000	-143.867732
15950000	-143.976856
16000000	-144.085638
16050000	-144.194081
16100000	-144.302186
16150000	-144.409955
16200000	-144.517392
16250000	-144.624497
16300000	-144.731272
16350000	-144.837721
16400000	-144.943844
16450000	-145.049644
16500000	-145.155123
16550000	-145.260282
16600000	-145.365124
16650000	-145.46965
16700000	-145.573863
16750000	-145.677764
16800000	-145.781355
16850000	-145.884638
16900000	-145.987614
16950000	-146.090287
17000000	-146.192656
17050000	-146.294725
17100000	-146.396495
17150000	-146.497968
17200000	-146.599145
17250000	-146.700028
17300000	-146.800619
17350000	-146.900919
17400000	-147.000931
17450000	-147.100655

Frequency Hz	Attenuation dB
17500000	-147.200094
17550000	-147.299249
17600000	-147.398122
17650000	-147.496714
17700000	-147.595027
17750000	-147.693063
17800000	-147.790822
17850000	-147.888308
17900000	-147.98552
17950000	-148.082461
18000000	-148.179132
18050000	-148.275535
18100000	-148.371672
18150000	-148.467542
18200000	-148.563149
18250000	-148.658494
18300000	-148.753577
18350000	-148.848401
18400000	-148.942967
18450000	-149.037276
18500000	-149.13133
18550000	-149.225129
18600000	-149.318676
18650000	-149.411972
18700000	-149.505018
18750000	-149.597815
18800000	-149.690365
18850000	-149.782669
18900000	-149.874729
18950000	-149.966545
19000000	-150.058119
19050000	-150.149452
19100000	-150.240546
19150000	-150.331401
19200000	-150.42202
19250000	-150.512402
19300000	-150.60255
19350000	-150.692465
19400000	-150.782147
19450000	-150.871599
19500000	-150.960821
19550000	-151.049814
19600000	-151.13858
19650000	-151.227119
19700000	-151.315434
19750000	-151.403524

Frequency Hz	Attenuation dB
19800000	-151.491392
19850000	-151.579038
19900000	-151.666463
19950000	-151.753669
20000000	-151.840656
20050000	-151.927426
20100000	-152.01398
20150000	-152.100319
20200000	-152.186444
20250000	-152.272355
20300000	-152.358055
20350000	-152.443544
20400000	-152.528823
20450000	-152.613893
20500000	-152.698755
20550000	-152.783411
20600000	-152.86786
20650000	-152.952105
20700000	-153.036146
20750000	-153.119984
20800000	-153.203621
20850000	-153.287056
20900000	-153.370292
20950000	-153.453328
21000000	-153.536166
21050000	-153.618808
21100000	-153.701253
21150000	-153.783503
21200000	-153.865559
21250000	-153.947421
21300000	-154.029091
21350000	-154.110569
21400000	-154.191857
21450000	-154.272955
21500000	-154.353864
21550000	-154.434585
21600000	-154.515119
21650000	-154.595466
21700000	-154.675629
21750000	-154.755606
21800000	-154.8354
21850000	-154.915011
21900000	-154.99444
21950000	-155.073688
22000000	-155.152755
22050000	-155.231643

Frequency Hz	Attenuation dB	Frequency Hz	Attenuation dB	Frequency Hz	Attenuation dB
22100000	-155.310352	24400000	-158.750736	26700000	-161.880887
22150000	-155.388883	24450000	-158.82187	26750000	-161.945897
22200000	-155.467237	24500000	-158.892858	26800000	-162.010786
22250000	-155.545414	24550000	-158.963702	26850000	-162.075554
22300000	-155.623417	24600000	-159.034401	26900000	-162.140201
22350000	-155.701244	24650000	-159.104957	26950000	-162.204729
22400000	-155.778897	24700000	-159.17537	27000000	-162.269136
22450000	-155.856377	24750000	-159.24564	27050000	-162.333425
22500000	-155.933685	24800000	-159.315769	27100000	-162.397594
22550000	-156.010821	24850000	-159.385756	27150000	-162.461646
22600000	-156.087786	24900000	-159.455603	27200000	-162.525579
22650000	-156.164581	24950000	-159.525309	27250000	-162.589395
22700000	-156.241207	25000000	-159.594876	27300000	-162.653094
22750000	-156.317664	25050000	-159.664304	27350000	-162.716676
22800000	-156.393953	25100000	-159.733593	27400000	-162.780143
22850000	-156.470075	25150000	-159.802744	27450000	-162.843493
22900000	-156.54603	25200000	-159.871758	27500000	-162.906728
22950000	-156.62182	25250000	-159.940636	27550000	-162.969849
23000000	-156.697444	25300000	-160.009376	27600000	-163.032855
23050000	-156.772905	25350000	-160.077981	27650000	-163.095746
23100000	-156.848202	25400000	-160.146451	27700000	-163.158524
23150000	-156.923336	25450000	-160.214787	27750000	-163.221189
23200000	-156.998307	25500000	-160.282988	27800000	-163.283741
23250000	-157.073118	25550000	-160.351055	27850000	-163.346181
23300000	-157.147767	25600000	-160.418989	27900000	-163.408509
23350000	-157.222257	25650000	-160.486791	27950000	-163.470724
23400000	-157.296587	25700000	-160.554461	28000000	-163.532829
23450000	-157.370759	25750000	-160.621999	28050000	-163.594823
23500000	-157.444772	25800000	-160.689406	28100000	-163.656707
23550000	-157.518628	25850000	-160.756682	28150000	-163.71848
23600000	-157.592327	25900000	-160.823829	28200000	-163.780144
23650000	-157.665871	25950000	-160.890845	28250000	-163.841698
23700000	-157.739259	26000000	-160.957733	28300000	-163.903144
23750000	-157.812492	26050000	-161.024493	28350000	-163.964481
23800000	-157.885571	26100000	-161.091124	28400000	-164.02571
23850000	-157.958497	26150000	-161.157628	28450000	-164.086831
23900000	-158.03127	26200000	-161.224004	28500000	-164.147845
23950000	-158.103891	26250000	-161.290254	28550000	-164.208752
24000000	-158.17636	26300000	-161.356378	28600000	-164.269553
24050000	-158.248678	26350000	-161.422377	28650000	-164.330247
24100000	-158.320847	26400000	-161.48825	28700000	-164.390835
24150000	-158.392865	26450000	-161.553998	28750000	-164.451318
24200000	-158.464735	26500000	-161.619623	28800000	-164.511696
24250000	-158.536456	26550000	-161.685123	28850000	-164.571969
24300000	-158.60803	26600000	-161.7505	28900000	-164.632137
24350000	-158.679456	26650000	-161.815755	28950000	-164.692202

Frequency Hz	Attenuation dB
29000000	-164.752163
29050000	-164.81202
29100000	-164.871775
29150000	-164.931427
29200000	-164.990977
29250000	-165.050424
29300000	-165.109771
29350000	-165.169016
29400000	-165.22816
29450000	-165.287204
29500000	-165.346147
29550000	-165.404991
29600000	-165.463735
29650000	-165.52238
29700000	-165.580926
29750000	-165.639374
29800000	-165.697723
29850000	-165.755975
29900000	-165.814129
29950000	-165.872186
30000000	-165.930146
30050000	-165.98801
30100000	-166.045777
30150000	-166.103448
30200000	-166.161024
30250000	-166.218505
30300000	-166.275891
30350000	-166.333182
30400000	-166.390378
30450000	-166.447481
30500000	-166.50449
30550000	-166.561405
30600000	-166.618228
30650000	-166.674958
30700000	-166.731595
30750000	-166.78814
30800000	-166.844593
30850000	-166.900954
30900000	-166.957225
30950000	-167.013404
31000000	-167.069492
31050000	-167.125491
31100000	-167.181399
31150000	-167.237217
31200000	-167.292945
31250000	-167.348585

Frequency Hz	Attenuation dB
31300000	-167.404135
31350000	-167.459597
31400000	-167.51497
31450000	-167.570256
31500000	-167.625453
31550000	-167.680563
31600000	-167.735585
31650000	-167.790521
31700000	-167.84537
31750000	-167.900132
31800000	-167.954808
31850000	-168.009398
31900000	-168.063903
31950000	-168.118322
32000000	-168.172656
32050000	-168.226905
32100000	-168.28107
32150000	-168.33515
32200000	-168.389147
32250000	-168.443059
32300000	-168.496888
32350000	-168.550634
32400000	-168.604296
32450000	-168.657876
32500000	-168.711374
32550000	-168.764789
32600000	-168.818122
32650000	-168.871373
32700000	-168.924543
32750000	-168.977632
32800000	-169.03064
32850000	-169.083566
32900000	-169.136413
32950000	-169.189179
33000000	-169.241865
33050000	-169.294471
33100000	-169.346998
33150000	-169.399445
33200000	-169.451814
33250000	-169.504103
33300000	-169.556314
33350000	-169.608447
33400000	-169.660502
33450000	-169.712478
33500000	-169.764377
33550000	-169.816199

Frequency Hz	Attenuation dB
33600000	-169.867943
33650000	-169.919611
33700000	-169.971201
33750000	-170.022716
33800000	-170.074153
33850000	-170.125515
33900000	-170.176801
33950000	-170.228012
34000000	-170.279147
34050000	-170.330207
34100000	-170.381192
34150000	-170.432102
34200000	-170.482938
34250000	-170.5337
34300000	-170.584387
34350000	-170.635001
34400000	-170.685541
34450000	-170.736007
34500000	-170.7864
34550000	-170.836721
34600000	-170.886968
34650000	-170.937143
34700000	-170.987246
34750000	-171.037277
34800000	-171.087235
34850000	-171.137122
34900000	-171.186937
34950000	-171.236681
35000000	-171.286354
35050000	-171.335956
35100000	-171.385487
35150000	-171.434948
35200000	-171.484338
35250000	-171.533658
35300000	-171.582909
35350000	-171.632089
35400000	-171.6812
35450000	-171.730242
35500000	-171.779215
35550000	-171.828118
35600000	-171.876953
35650000	-171.92572
35700000	-171.974418
35750000	-172.023048
35800000	-172.071609
35850000	-172.120103

Frequency Hz		Attenuation dB
35900000		-172.16853
35950000		-172.216889
36000000		-172.265181
36050000		-172.313406
36100000		-172.361564
36150000		-172.409655
36200000		-172.45768
36250000		-172.505638
36300000		-172.553531
36350000		-172.601357
36400000		-172.649118
36450000		-172.696813
36500000		-172.744443
36550000		-172.792008
36600000		-172.839507
36650000		-172.886942
36700000		-172.934312
36750000		-172.981617
36800000		-173.028859
36850000		-173.076036
36900000		-173.123149
36950000		-173.170198
37000000		-173.217184
37050000		-173.264106
37100000		-173.310965
37150000		-173.35776
37200000		-173.404493
37250000		-173.451163
37300000		-173.497771
37350000		-173.544316
37400000		-173.590798
37450000		-173.637219
37500000		-173.683578
37550000		-173.729875
37600000		-173.77611
37650000		-173.822284
37700000		-173.868396
37750000		-173.914447
37800000		-173.960438
37850000		-174.006368
37900000		-174.052237
37950000		-174.098045
38000000		-174.143793
38050000		-174.189481
38100000		-174.235109
38150000		-174.280677

Frequency Hz		Attenuation dB
38200000		-174.326186
38250000		-174.371635
38300000		-174.417024
38350000		-174.462355
38400000		-174.507626
38450000		-174.552838
38500000		-174.597992
38550000		-174.643087
38600000		-174.688124
38650000		-174.733102
38700000		-174.778022
38750000		-174.822884
38800000		-174.867688
38850000		-174.912435
38900000		-174.957124
38950000		-175.001755
39000000		-175.046329
39050000		-175.090846
39100000		-175.135307
39150000		-175.17971
39200000		-175.224057
39250000		-175.268347
39300000		-175.312581
39350000		-175.356758
39400000		-175.400879
39450000		-175.444945
39500000		-175.488954
39550000		-175.532908
39600000		-175.576807
39650000		-175.62065
39700000		-175.664438
39750000		-175.70817
39800000		-175.751848
39850000		-175.795471
39900000		-175.839039
39950000		-175.882552
40000000		-175.926011
40050000		-175.969416
40100000		-176.012767
40150000		-176.056063
40200000		-176.099306
40250000		-176.142495
40300000		-176.18563
40350000		-176.228712
40400000		-176.271741
40450000		-176.314716

Frequency Hz		Attenuation dB
40500000		-176.357638
40550000		-176.400507
40600000		-176.443324
40650000		-176.486087
40700000		-176.528798
40750000		-176.571457
40800000		-176.614063
40850000		-176.656617
40900000		-176.699119
40950000		-176.74157
41000000		-176.783968
41050000		-176.826315
41100000		-176.86861
41150000		-176.910853
41200000		-176.953046
41250000		-176.995187
41300000		-177.037277
41350000		-177.079316
41400000		-177.121305
41450000		-177.163242
41500000		-177.20513
41550000		-177.246966
41600000		-177.288753
41650000		-177.330489
41700000		-177.372175
41750000		-177.413811
41800000		-177.455397
41850000		-177.496934
41900000		-177.538421
41950000		-177.579859
42000000		-177.621247
42050000		-177.662586
42100000		-177.703875
42150000		-177.745116
42200000		-177.786308
42250000		-177.827451
42300000		-177.868546
42350000		-177.909591
42400000		-177.950589
42450000		-177.991538
42500000		-178.032439
42550000		-178.073292
42600000		-178.114096
42650000		-178.154853
42700000		-178.195563
42750000		-178.236224

Frequency Hz	Attenuation dB
42800000	-178.276838
42850000	-178.317405
42900000	-178.357924
42950000	-178.398396
43000000	-178.438821
43050000	-178.479199
43100000	-178.51953
43150000	-178.559815
43200000	-178.600052
43250000	-178.640243
43300000	-178.680388
43350000	-178.720486
43400000	-178.760539
43450000	-178.800545
43500000	-178.840505
43550000	-178.880419
43600000	-178.920287
43650000	-178.96011
43700000	-178.999887
43750000	-179.039618
43800000	-179.079304
43850000	-179.118945
43900000	-179.158541
43950000	-179.198091
44000000	-179.237597
44050000	-179.277058
44100000	-179.316474
44150000	-179.355845
44200000	-179.395172
44250000	-179.434454
44300000	-179.473692
44350000	-179.512886
44400000	-179.552035
44450000	-179.591141
44500000	-179.630202
44550000	-179.66922
44600000	-179.708193
44650000	-179.747123
44700000	-179.78601
44750000	-179.824853
44800000	-179.863653
44850000	-179.902409
44900000	-179.941122
44950000	-179.979793
45000000	-180.01842
45050000	-180.057004

Frequency Hz	Attenuation dB
45100000	-180.095545
45150000	-180.134044
45200000	-180.1725
45250000	-180.210914
45300000	-180.249285
45350000	-180.287614
45400000	-180.325901
45450000	-180.364145
45500000	-180.402347
45550000	-180.440508
45600000	-180.478626
45650000	-180.516703
45700000	-180.554738
45750000	-180.592732
45800000	-180.630684
45850000	-180.668594
45900000	-180.706464
45950000	-180.744292
46000000	-180.782079
46050000	-180.819825
46100000	-180.857529
46150000	-180.895193
46200000	-180.932817
46250000	-180.970399
46300000	-181.007941
46350000	-181.045442
46400000	-181.082903
46450000	-181.120324
46500000	-181.157704
46550000	-181.195044
46600000	-181.232345
46650000	-181.269605
46700000	-181.306825
46750000	-181.344005
46800000	-181.381146
46850000	-181.418247
46900000	-181.455308
46950000	-181.49233
47000000	-181.529312
47050000	-181.566255
47100000	-181.603159
47150000	-181.640024
47200000	-181.676849
47250000	-181.713636
47300000	-181.750384
47350000	-181.787093

Frequency Hz	Attenuation dB
47400000	-181.823763
47450000	-181.860394
47500000	-181.896987
47550000	-181.933542
47600000	-181.970058
47650000	-182.006535
47700000	-182.042975
47750000	-182.079376
47800000	-182.115739
47850000	-182.152064
47900000	-182.188351
47950000	-182.2246
48000000	-182.260812
48050000	-182.296986
48100000	-182.333122
48150000	-182.36922
48200000	-182.405282
48250000	-182.441305
48300000	-182.477292
48350000	-182.513241
48400000	-182.549153
48450000	-182.585028
48500000	-182.620866
48550000	-182.656667
48600000	-182.692431
48650000	-182.728159
48700000	-182.763849
48750000	-182.799503
48800000	-182.835121
48850000	-182.870702
48900000	-182.906247
48950000	-182.941755
49000000	-182.977227
49050000	-183.012663
49100000	-183.048063
49150000	-183.083426
49200000	-183.118754
49250000	-183.154046
49300000	-183.189302
49350000	-183.224522
49400000	-183.259707
49450000	-183.294856
49500000	-183.32997
49550000	-183.365048
49600000	-183.40009
49650000	-183.435098

Frequency Hz		Attenuation dB
49700000		-183.47007
49750000		-183.505007
49800000		-183.539909
49850000		-183.574776
49900000		-183.609608
49950000		-183.644405
50000000		-183.679167
50050000		-183.713894
50100000		-183.748587
50150000		-183.783245
50200000		-183.817869
50250000		-183.852458
50300000		-183.887013
50350000		-183.921533
50400000		-183.956019
50450000		-183.990471
50500000		-184.024889
50550000		-184.059273
50600000		-184.093623
50650000		-184.127939
50700000		-184.162221
50750000		-184.196469
50800000		-184.230683
50850000		-184.264864
50900000		-184.299011
50950000		-184.333125
51000000		-184.367205
51050000		-184.401252
51100000		-184.435265
51150000		-184.469246
51200000		-184.503193
51250000		-184.537106
51300000		-184.570987
51350000		-184.604835
51400000		-184.63865
51450000		-184.672432
51500000		-184.706181
51550000		-184.739897
51600000		-184.773581
51650000		-184.807232
51700000		-184.840851
51750000		-184.874437
51800000		-184.90799
51850000		-184.941512
51900000		-184.975
51950000		-185.008457

Frequency Hz		Attenuation dB
52000000		-185.041882
52050000		-185.075274
52100000		-185.108634
52150000		-185.141962
52200000		-185.175259
52250000		-185.208523
52300000		-185.241756
52350000		-185.274957
52400000		-185.308126
52450000		-185.341263
52500000		-185.374369
52550000		-185.407444
52600000		-185.440487
52650000		-185.473498
52700000		-185.506479
52750000		-185.539428
52800000		-185.572345
52850000		-185.605232
52900000		-185.638088
52950000		-185.670912
53000000		-185.703705
53050000		-185.736468
53100000		-185.7692
53150000		-185.801901
53200000		-185.834571
53250000		-185.86721
53300000		-185.899819
53350000		-185.932397
53400000		-185.964945
53450000		-185.997462
53500000		-186.029949
53550000		-186.062405
53600000		-186.094832
53650000		-186.127227
53700000		-186.159593
53750000		-186.191929
53800000		-186.224234
53850000		-186.25651
53900000		-186.288756
53950000		-186.320971
54000000		-186.353157
54050000		-186.385313
54100000		-186.41744
54150000		-186.449536
54200000		-186.481603
54250000		-186.513641

Frequency Hz		Attenuation dB
54300000		-186.545649
54350000		-186.577627
54400000		-186.609576
54450000		-186.641496
54500000		-186.673387
54550000		-186.705248
54600000		-186.73708
54650000		-186.768883
54700000		-186.800656
54750000		-186.832401
54800000		-186.864117
54850000		-186.895804
54900000		-186.927462
54950000		-186.959091
55000000		-186.990691
55050000		-187.022263
55100000		-187.053806
55150000		-187.08532
55200000		-187.116806
55250000		-187.148263
55300000		-187.179692
55350000		-187.211093
55400000		-187.242465
55450000		-187.273808
55500000		-187.305124
55550000		-187.336411
55600000		-187.36767
55650000		-187.398902
55700000		-187.430105
55750000		-187.46128
55800000		-187.492427
55850000		-187.523546
55900000		-187.554637
55950000		-187.585701
56000000		-187.616737
56050000		-187.647745
56100000		-187.678725
56150000		-187.709678
56200000		-187.740603
56250000		-187.771501
56300000		-187.802371
56350000		-187.833214
56400000		-187.86403
56450000		-187.894818
56500000		-187.925579
56550000		-187.956313

Frequency Hz	Attenuation dB
56600000	-187.987019
56650000	-188.017699
56700000	-188.048351
56750000	-188.078977
56800000	-188.109575
56850000	-188.140147
56900000	-188.170691
56950000	-188.201209
57000000	-188.2317
57050000	-188.262165
57100000	-188.292602
57150000	-188.323013
57200000	-188.353398
57250000	-188.383755
57300000	-188.414087
57350000	-188.444392
57400000	-188.47467
57450000	-188.504922
57500000	-188.535148
57550000	-188.565347
57600000	-188.595521
57650000	-188.625668
57700000	-188.655789
57750000	-188.685883
57800000	-188.715952
57850000	-188.745995
57900000	-188.776012
57950000	-188.806003
58000000	-188.835968
58050000	-188.865907
58100000	-188.895821
58150000	-188.925708
58200000	-188.95557
58250000	-188.985407
58300000	-189.015218
58350000	-189.045003
58400000	-189.074763
58450000	-189.104497
58500000	-189.134206
58550000	-189.163889
58600000	-189.193547
58650000	-189.22318
58700000	-189.252788
58750000	-189.28237
58800000	-189.311927
58850000	-189.341459

Frequency Hz	Attenuation dB
58900000	-189.370966
58950000	-189.400448
59000000	-189.429905
59050000	-189.459337
59100000	-189.488744
59150000	-189.518126
59200000	-189.547484
59250000	-189.576816
59300000	-189.606124
59350000	-189.635407
59400000	-189.664666
59450000	-189.6939
59500000	-189.723109
59550000	-189.752294
59600000	-189.781454
59650000	-189.81059
59700000	-189.839701
59750000	-189.868788
59800000	-189.897851
59850000	-189.926889
59900000	-189.955903
59950000	-189.984893
60000000	-190.013859
60050000	-190.042801
60100000	-190.071718
60150000	-190.100612
60200000	-190.129481
60250000	-190.158327
60300000	-190.187148
60350000	-190.215946
60400000	-190.24472
60450000	-190.27347
60500000	-190.302196
60550000	-190.330899
60600000	-190.359578
60650000	-190.388233
60700000	-190.416864
60750000	-190.445472
60800000	-190.474057
60850000	-190.502618
60900000	-190.531155
60950000	-190.559669
61000000	-190.58816
61050000	-190.616628
61100000	-190.645072
61150000	-190.673492

Frequency Hz	Attenuation dB
61200000	-190.70189
61250000	-190.730264
61300000	-190.758615
61350000	-190.786944
61400000	-190.815249
61450000	-190.843531
61500000	-190.87179
61550000	-190.900026
61600000	-190.928239
61650000	-190.956429
61700000	-190.984596
61750000	-191.012741
61800000	-191.040862
61850000	-191.068961
61900000	-191.097038
61950000	-191.125091
62000000	-191.153122
62050000	-191.18113
62100000	-191.209116
62150000	-191.23708
62200000	-191.26502
62250000	-191.292939
62300000	-191.320835
62350000	-191.348708
62400000	-191.376559
62450000	-191.404388
62500000	-191.432195
62550000	-191.459979
62600000	-191.487741
62650000	-191.515481
62700000	-191.543199
62750000	-191.570895
62800000	-191.598569
62850000	-191.626221
62900000	-191.65385
62950000	-191.681458
63000000	-191.709044
63050000	-191.736608
63100000	-191.76415
63150000	-191.79167
63200000	-191.819169
63250000	-191.846645
63300000	-191.8741
63350000	-191.901534
63400000	-191.928945
63450000	-191.956336

Frequency Hz		Attenuation dB
63500000		-191.983704
63550000		-192.011051
63600000		-192.038377
63650000		-192.065681
63700000		-192.092963
63750000		-192.120224
63800000		-192.147464
63850000		-192.174682
63900000		-192.20188
63950000		-192.229055
64000000		-192.25621
64050000		-192.283343
64100000		-192.310456
64150000		-192.337547
64200000		-192.364617
64250000		-192.391666
64300000		-192.418694
64350000		-192.4457
64400000		-192.472686
64450000		-192.499651
64500000		-192.526595
64550000		-192.553518
64600000		-192.580421
64650000		-192.607302
64700000		-192.634163
64750000		-192.661003
64800000		-192.687822
64850000		-192.714621
64900000		-192.741399
64950000		-192.768156
65000000		-192.794892
65050000		-192.821609
65100000		-192.848304
65150000		-192.874979
65200000		-192.901634
65250000		-192.928268
65300000		-192.954882
65350000		-192.981475
65400000		-193.008048
65450000		-193.034601
65500000		-193.061134
65550000		-193.087646
65600000		-193.114138
65650000		-193.14061
65700000		-193.167061
65750000		-193.193493

Frequency Hz		Attenuation dB
65800000		-193.219904
65850000		-193.246296
65900000		-193.272667
65950000		-193.299019
66000000		-193.32535
66050000		-193.351661
66100000		-193.377953
66150000		-193.404225
66200000		-193.430476
66250000		-193.456708
66300000		-193.482921
66350000		-193.509113
66400000		-193.535286
66450000		-193.561439
66500000		-193.587572
66550000		-193.613686
66600000		-193.63978
66650000		-193.665854
66700000		-193.691909
66750000		-193.717945
66800000		-193.743961
66850000		-193.769957
66900000		-193.795934
66950000		-193.821892
67000000		-193.84783
67050000		-193.873749
67100000		-193.899649
67150000		-193.925529
67200000		-193.95139
67250000		-193.977232
67300000		-194.003054
67350000		-194.028857
67400000		-194.054642
67450000		-194.080407
67500000		-194.106153
67550000		-194.13188
67600000		-194.157588
67650000		-194.183277
67700000		-194.208947
67750000		-194.234598
67800000		-194.26023
67850000		-194.285843
67900000		-194.311437
67950000		-194.337012
68000000		-194.362569
68050000		-194.388107

Frequency Hz		Attenuation dB
68100000		-194.413626
68150000		-194.439126
68200000		-194.464608
68250000		-194.490071
68300000		-194.515515
68350000		-194.540941
68400000		-194.566348
68450000		-194.591737
68500000		-194.617107
68550000		-194.642458
68600000		-194.667791
68650000		-194.693106
68700000		-194.718402
68750000		-194.74368
68800000		-194.768939
68850000		-194.79418
68900000		-194.819403
68950000		-194.844607
69000000		-194.869793
69050000		-194.894961
69100000		-194.920111
69150000		-194.945242
69200000		-194.970355
69250000		-194.995451
69300000		-195.020528
69350000		-195.045586
69400000		-195.070627
69450000		-195.09565
69500000		-195.120655
69550000		-195.145642
69600000		-195.170611
69650000		-195.195562
69700000		-195.220495
69750000		-195.24541
69800000		-195.270307
69850000		-195.295187
69900000		-195.320048
69950000		-195.344892
70000000		-195.369718
70050000		-195.394527
70100000		-195.419318
70150000		-195.444091
70200000		-195.468846
70250000		-195.493584
70300000		-195.518304
70350000		-195.543007

Frequency Hz	Attenuation dB	Frequency Hz	Attenuation dB	Frequency Hz	Attenuation dB
70400000	-195.567692	72700000	-196.684652	75000000	-197.766818
70450000	-195.592359	72750000	-196.708539	75050000	-197.789973
70500000	-195.617009	72800000	-196.73241	75100000	-197.813112
70550000	-195.641642	72850000	-196.756264	75150000	-197.836237
70600000	-195.666257	72900000	-196.780103	75200000	-197.859345
70650000	-195.690854	72950000	-196.803924	75250000	-197.882439
70700000	-195.715435	73000000	-196.82773	75300000	-197.905517
70750000	-195.739998	73050000	-196.851519	75350000	-197.92858
70800000	-195.764543	73100000	-196.875292	75400000	-197.951627
70850000	-195.789071	73150000	-196.899049	75450000	-197.97466
70900000	-195.813582	73200000	-196.922789	75500000	-197.997677
70950000	-195.838076	73250000	-196.946514	75550000	-198.020678
71000000	-195.862552	73300000	-196.970222	75600000	-198.043665
71050000	-195.887011	73350000	-196.993913	75650000	-198.066636
71100000	-195.911453	73400000	-197.017589	75700000	-198.089592
71150000	-195.935878	73450000	-197.041249	75750000	-198.112533
71200000	-195.960286	73500000	-197.064892	75800000	-198.135459
71250000	-195.984676	73550000	-197.08852	75850000	-198.15837
71300000	-196.009049	73600000	-197.112131	75900000	-198.181265
71350000	-196.033406	73650000	-197.135726	75950000	-198.204146
71400000	-196.057745	73700000	-197.159306	76000000	-198.227011
71450000	-196.082067	73750000	-197.182869	76050000	-198.249862
71500000	-196.106372	73800000	-197.206417	76100000	-198.272697
71550000	-196.13066	73850000	-197.229948	76150000	-198.295518
71600000	-196.154931	73900000	-197.253463	76200000	-198.318323
71650000	-196.179186	73950000	-197.276963	76250000	-198.341114
71700000	-196.203423	74000000	-197.300447	76300000	-198.363889
71750000	-196.227643	74050000	-197.323915	76350000	-198.38665
71800000	-196.251847	74100000	-197.347367	76400000	-198.409396
71850000	-196.276033	74150000	-197.370803	76450000	-198.432126
71900000	-196.300203	74200000	-197.394223	76500000	-198.454842
71950000	-196.324356	74250000	-197.417628	76550000	-198.477544
72000000	-196.348493	74300000	-197.441017	76600000	-198.50023
72050000	-196.372612	74350000	-197.46439	76650000	-198.522901
72100000	-196.396715	74400000	-197.487747	76700000	-198.545558
72150000	-196.420801	74450000	-197.511089	76750000	-198.5682
72200000	-196.44487	74500000	-197.534415	76800000	-198.590827
72250000	-196.468923	74550000	-197.557725	76850000	-198.61344
72300000	-196.492959	74600000	-197.58102	76900000	-198.636038
72350000	-196.516979	74650000	-197.604299	76950000	-198.658621
72400000	-196.540982	74700000	-197.627563	77000000	-198.681189
72450000	-196.564968	74750000	-197.650811	77050000	-198.703743
72500000	-196.588938	74800000	-197.674043	77100000	-198.726282
72550000	-196.612891	74850000	-197.69726	77150000	-198.748807
72600000	-196.636828	74900000	-197.720461	77200000	-198.771317
72650000	-196.660748	74950000	-197.743647	77250000	-198.793812

Frequency Hz		Attenuation dB
77300000		-198.816293
77350000		-198.838759
77400000		-198.861211
77450000		-198.883648
77500000		-198.906071
77550000		-198.928479
77600000		-198.950873
77650000		-198.973252
77700000		-198.995617
77750000		-199.017968
77800000		-199.040304
77850000		-199.062626
77900000		-199.084934
77950000		-199.107227
78000000		-199.129506
78050000		-199.151771
78100000		-199.174021
78150000		-199.196257
78200000		-199.218479
78250000		-199.240687
78300000		-199.262881
78350000		-199.28506
78400000		-199.307226
78450000		-199.329377
78500000		-199.351514
78550000		-199.373637
78600000		-199.395746
78650000		-199.41784
78700000		-199.439921
78750000		-199.461988
78800000		-199.484041
78850000		-199.506079
78900000		-199.528104
78950000		-199.550115
79000000		-199.572112
79050000		-199.594095
79100000		-199.616064
79150000		-199.638019
79200000		-199.65996
79250000		-199.681888
79300000		-199.703801
79350000		-199.725701
79400000		-199.747587
79450000		-199.769459
79500000		-199.791318
79550000		-199.813163

Frequency Hz		Attenuation dB
79600000		-199.834994
79650000		-199.856811
79700000		-199.878615
79750000		-199.900404
79800000		-199.922181
79850000		-199.943943
79900000		-199.965692
79950000		-199.987428
80000000		-200.00915
80050000		-200.030858
80100000		-200.052553
80150000		-200.074234
80200000		-200.095901
80250000		-200.117555
80300000		-200.139196
80350000		-200.160823
80400000		-200.182437
80450000		-200.204037
80500000		-200.225624
80550000		-200.247198
80600000		-200.268758
80650000		-200.290304
80700000		-200.311838
80750000		-200.333358
80800000		-200.354864
80850000		-200.376358
80900000		-200.397838
80950000		-200.419305
81000000		-200.440758
81050000		-200.462199
81100000		-200.483626
81150000		-200.50504
81200000		-200.52644
81250000		-200.547828
81300000		-200.569202
81350000		-200.590563
81400000		-200.611911
81450000		-200.633246
81500000		-200.654568
81550000		-200.675877
81600000		-200.697173
81650000		-200.718456
81700000		-200.739725
81750000		-200.760982
81800000		-200.782226
81850000		-200.803456

Frequency Hz		Attenuation dB
81900000		-200.824674
81950000		-200.845879
82000000		-200.867071
82050000		-200.88825
82100000		-200.909416
82150000		-200.930569
82200000		-200.951709
82250000		-200.972836
82300000		-200.993951
82350000		-201.015053
82400000		-201.036142
82450000		-201.057218
82500000		-201.078281
82550000		-201.099332
82600000		-201.12037
82650000		-201.141395
82700000		-201.162407
82750000		-201.183407
82800000		-201.204394
82850000		-201.225368
82900000		-201.24633
82950000		-201.267279
83000000		-201.288216
83050000		-201.309139
83100000		-201.330051
83150000		-201.350949
83200000		-201.371835
83250000		-201.392709
83300000		-201.41357
83350000		-201.434418
83400000		-201.455254
83450000		-201.476078
83500000		-201.496889
83550000		-201.517687
83600000		-201.538474
83650000		-201.559247
83700000		-201.580009
83750000		-201.600757
83800000		-201.621494
83850000		-201.642218
83900000		-201.66293
83950000		-201.683629
84000000		-201.704316
84050000		-201.724991
84100000		-201.745654
84150000		-201.766304

Frequency Hz		Attenuation dB
84200000		-201.786942
84250000		-201.807568
84300000		-201.828181
84350000		-201.848782
84400000		-201.869371
84450000		-201.889948
84500000		-201.910513
84550000		-201.931065
84600000		-201.951606
84650000		-201.972134
84700000		-201.99265
84750000		-202.013154
84800000		-202.033646
84850000		-202.054126
84900000		-202.074593
84950000		-202.095049
85000000		-202.115493
85050000		-202.135924
85100000		-202.156344
85150000		-202.176752
85200000		-202.197147
85250000		-202.217531
85300000		-202.237903
85350000		-202.258263
85400000		-202.27861
85450000		-202.298946
85500000		-202.319271
85550000		-202.339583
85600000		-202.359883
85650000		-202.380171
85700000		-202.400448
85750000		-202.420713
85800000		-202.440966
85850000		-202.461207
85900000		-202.481436
85950000		-202.501654
86000000		-202.52186
86050000		-202.542054
86100000		-202.562236
86150000		-202.582407
86200000		-202.602566
86250000		-202.622713
86300000		-202.642849
86350000		-202.662973
86400000		-202.683085
86450000		-202.703186

Frequency Hz		Attenuation dB
86500000		-202.723275
86550000		-202.743352
86600000		-202.763418
86650000		-202.783472
86700000		-202.803515
86750000		-202.823546
86800000		-202.843566
86850000		-202.863574
86900000		-202.88357
86950000		-202.903555
87000000		-202.923529
87050000		-202.943491
87100000		-202.963442
87150000		-202.983381
87200000		-203.003308
87250000		-203.023225
87300000		-203.04313
87350000		-203.063023
87400000		-203.082905
87450000		-203.102776
87500000		-203.122635
87550000		-203.142483
87600000		-203.16232
87650000		-203.182145
87700000		-203.201959
87750000		-203.221762
87800000		-203.241554
87850000		-203.261334
87900000		-203.281103
87950000		-203.300861
88000000		-203.320607
88050000		-203.340342
88100000		-203.360067
88150000		-203.379779
88200000		-203.399481
88250000		-203.419172
88300000		-203.438851
88350000		-203.458519
88400000		-203.478176
88450000		-203.497822
88500000		-203.517457
88550000		-203.537081
88600000		-203.556694
88650000		-203.576296
88700000		-203.595886
88750000		-203.615466

Frequency Hz		Attenuation dB
88800000		-203.635034
88850000		-203.654592
88900000		-203.674138
88950000		-203.693674
89000000		-203.713198
89050000		-203.732712
89100000		-203.752215
89150000		-203.771706
89200000		-203.791187
89250000		-203.810657
89300000		-203.830116
89350000		-203.849564
89400000		-203.869001
89450000		-203.888428
89500000		-203.907843
89550000		-203.927248
89600000		-203.946641
89650000		-203.966024
89700000		-203.985396
89750000		-204.004758
89800000		-204.024108
89850000		-204.043448
89900000		-204.062777
89950000		-204.082096
90000000		-204.101403
90050000		-204.1207
90100000		-204.139986
90150000		-204.159261
90200000		-204.178526
90250000		-204.19778
90300000		-204.217024
90350000		-204.236256
90400000		-204.255479
90450000		-204.27469
90500000		-204.293891
90550000		-204.313081
90600000		-204.332261
90650000		-204.35143
90700000		-204.370588
90750000		-204.389736
90800000		-204.408874
90850000		-204.428001
90900000		-204.447117
90950000		-204.466223
91000000		-204.485318
91050000		-204.504403

Frequency Hz	Attenuation dB
91100000	-204.523477
91150000	-204.542541
91200000	-204.561595
91250000	-204.580637
91300000	-204.59967
91350000	-204.618692
91400000	-204.637704
91450000	-204.656705
91500000	-204.675696
91550000	-204.694677
91600000	-204.713647
91650000	-204.732607
91700000	-204.751556
91750000	-204.770496
91800000	-204.789424
91850000	-204.808343
91900000	-204.827251
91950000	-204.846149
92000000	-204.865037
92050000	-204.883914
92100000	-204.902782
92150000	-204.921638
92200000	-204.940485
92250000	-204.959322
92300000	-204.978148
92350000	-204.996964
92400000	-205.01577
92450000	-205.034566
92500000	-205.053351
92550000	-205.072127
92600000	-205.090892
92650000	-205.109647
92700000	-205.128392
92750000	-205.147127
92800000	-205.165852
92850000	-205.184567
92900000	-205.203271
92950000	-205.221966
93000000	-205.240651
93050000	-205.259325
93100000	-205.27799
93150000	-205.296644
93200000	-205.315288
93250000	-205.333923
93300000	-205.352547
93350000	-205.371162

Frequency Hz	Attenuation dB
93400000	-205.389766
93450000	-205.408361
93500000	-205.426946
93550000	-205.44552
93600000	-205.464085
93650000	-205.48264
93700000	-205.501185
93750000	-205.51972
93800000	-205.538245
93850000	-205.55676
93900000	-205.575266
93950000	-205.593761
94000000	-205.612247
94050000	-205.630723
94100000	-205.649189
94150000	-205.667645
94200000	-205.686092
94250000	-205.704528
94300000	-205.722955
94350000	-205.741372
94400000	-205.75978
94450000	-205.778177
94500000	-205.796565
94550000	-205.814943
94600000	-205.833312
94650000	-205.85167
94700000	-205.87002
94750000	-205.888359
94800000	-205.906689
94850000	-205.925009
94900000	-205.943319
94950000	-205.96162
95000000	-205.979911
95050000	-205.998192
95100000	-206.016464
95150000	-206.034726
95200000	-206.052979
95250000	-206.071222
95300000	-206.089455
95350000	-206.107679
95400000	-206.125894
95450000	-206.144099
95500000	-206.162294
95550000	-206.18048
95600000	-206.198656
95650000	-206.216823

Frequency Hz	Attenuation dB
95700000	-206.23498
95750000	-206.253128
95800000	-206.271266
95850000	-206.289395
95900000	-206.307514
95950000	-206.325624
96000000	-206.343725
96050000	-206.361816
96100000	-206.379897
96150000	-206.39797
96200000	-206.416032
96250000	-206.434086
96300000	-206.45213
96350000	-206.470165
96400000	-206.48819
96450000	-206.506206
96500000	-206.524213
96550000	-206.54221
96600000	-206.560198
96650000	-206.578177
96700000	-206.596146
96750000	-206.614106
96800000	-206.632057
96850000	-206.649999
96900000	-206.667931
96950000	-206.685854
97000000	-206.703768
97050000	-206.721673
97100000	-206.739568
97150000	-206.757454
97200000	-206.775331
97250000	-206.793199
97300000	-206.811058
97350000	-206.828907
97400000	-206.846747
97450000	-206.864578
97500000	-206.8824
97550000	-206.900213
97600000	-206.918017
97650000	-206.935811
97700000	-206.953597
97750000	-206.971373
97800000	-206.989141
97850000	-207.006899
97900000	-207.024648
97950000	-207.042388

Frequency Hz		Attenuation dB
98000000		-207.060119
98050000		-207.077841
98100000		-207.095554
98150000		-207.113258
98200000		-207.130953
98250000		-207.148638
98300000		-207.166315
98350000		-207.183983
98400000		-207.201642
98450000		-207.219292
98500000		-207.236933
98550000		-207.254565
98600000		-207.272188
98650000		-207.289802
98700000		-207.307407
98750000		-207.325004
98800000		-207.342591
98850000		-207.36017
98900000		-207.377739
98950000		-207.3953
99000000		-207.412852
99050000		-207.430395
99100000		-207.447929
99150000		-207.465454
99200000		-207.482971
99250000		-207.500478
99300000		-207.517977
99350000		-207.535467
99400000		-207.552948
99450000		-207.570421
99500000		-207.587884
99550000		-207.605339
99600000		-207.622785
99650000		-207.640222
99700000		-207.657651
99750000		-207.675071
99800000		-207.692482
99850000		-207.709884
99900000		-207.727278
99950000		-207.744663
1E+08		-207.762039

Appendix 2: Results from equation 5.21

The following table presents the results used to generate figure 5.17.

Frequency Hz		Attenuation dB	Frequency Hz		Attenuation dB	Frequency Hz		Attenuation dB
1		3.1849E-10	4500000		-54.33776399	9000000		-53.53313576
100000		3.176086819	4600000		-54.29047284	9100000		-53.52742515
200000		1.736957663	4700000		-54.24629911	9200000		-53.52190177
300000		-2.27413258	4800000		-54.20497203	9300000		-53.51655749
400000		-0.58763525	4900000		-54.16624986	9400000		-53.51138463
500000		-20.66735309	5000000		-54.12991623	9500000		-53.50637593
600000		-32.12233349	5100000		-54.09577694	9600000		-53.50152449
700000		-41.64851204	5200000		-54.06365734	9700000		-53.49682378
800000		-50.83097194	5300000		-54.0333999	9800000		-53.49226761
900000		-60.85819864	5400000		-54.00486232	9900000		-53.4878501
1000000		-73.92044611	5500000		-53.9779157	10000000		-53.48356567
1100000		-101.7213533	5600000		-53.9524431	10100000		-53.479409
1200000		-90.34236571	5700000		-53.92833819	10200000		-53.47537507
1300000		-76.980446	5800000		-53.90550414	10300000		-53.47145908
1400000		-70.90160317	5900000		-53.88385258	10400000		-53.46765645
1500000		-67.23226553	6000000		-53.86330273	10500000		-53.46396286
1600000		-64.74026954	6100000		-53.84378065	10600000		-53.46037416
1700000		-62.92993082	6200000		-53.82521853	10700000		-53.45688641
1800000		-61.55499758	6300000		-53.8075541	10800000		-53.45349586
1900000		-60.4768449	6400000		-53.79073006	10900000		-53.45019891
2000000		-59.61062205	6500000		-53.77469366	11000000		-53.44699215
2100000		-58.90116097	6600000		-53.75939624	11100000		-53.4438723
2200000		-58.31091156	6700000		-53.74479286	11200000		-53.44083627
2300000		-57.81337672	6800000		-53.73084195	11300000		-53.43788105
2400000		-57.38930452	6900000		-53.71750503	11400000		-53.43500381
2500000		-57.02436435	7000000		-53.70474644	11500000		-53.43220182
2600000		-56.70766873	7100000		-53.69253305	11600000		-53.42947247
2700000		-56.4308	7200000		-53.68083412	11700000		-53.42681327
2800000		-56.18715048	7300000		-53.66962102	11800000		-53.42422184
2900000		-55.97146369	7400000		-53.65886711	11900000		-53.42169588
3000000		-55.77950853	7500000		-53.64854757	12000000		-53.41923321
3100000		-55.60784318	7600000		-53.63863921	12100000		-53.41683173
3200000		-55.45364129	7700000		-53.62912039	12200000		-53.41448941
3300000		-55.31456199	7800000		-53.61997089	12300000		-53.41220434
3400000		-55.18865134	7900000		-53.61117178	12400000		-53.40997466
3500000		-55.07426678	8000000		-53.60270532	12500000		-53.40779859
3600000		-54.97001843	8100000		-53.59455491	12600000		-53.40567442
3700000		-54.87472316	8200000		-53.58670494	12700000		-53.40360051
3800000		-54.78736817	8300000		-53.5791408	12800000		-53.40157529
3900000		-54.70708203	8400000		-53.57184871	12900000		-53.39959725
4000000		-54.6331113	8500000		-53.56481576	13000000		-53.39766492
4100000		-54.56480163	8600000		-53.55802977	13100000		-53.39577691
4200000		-54.50158235	8700000		-53.55147927	13200000		-53.39393187
4300000		-54.44295376	8800000		-53.54515347	13300000		-53.39212851
4400000		-54.38847674	8900000		-53.53904217	13400000		-53.39036557

Frequency Hz	Attenuation dB
13500000	-53.38864187
13600000	-53.38695623
13700000	-53.38530755
13800000	-53.38369475
13900000	-53.38211679
14000000	-53.38057269
14100000	-53.37906147
14200000	-53.37758222
14300000	-53.37613402
14400000	-53.37471603
14500000	-53.37332739
14600000	-53.37196732
14700000	-53.37063502
14800000	-53.36932975
14900000	-53.36805078
15000000	-53.36679741
15100000	-53.36556896
15200000	-53.36436477
15300000	-53.3631842
15400000	-53.36202665
15500000	-53.36089151
15600000	-53.35977821
15700000	-53.3586862
15800000	-53.35761493
15900000	-53.35656389
16000000	-53.35553256
16100000	-53.35452045
16200000	-53.35352709
16300000	-53.35255203
16400000	-53.3515948
16500000	-53.35065499
16600000	-53.34973216
16700000	-53.34882592
16800000	-53.34793586
16900000	-53.3470616
17000000	-53.34620278
17100000	-53.34535903
17200000	-53.34453
17300000	-53.34371534
17400000	-53.34291473
17500000	-53.34212785
17600000	-53.34135438
17700000	-53.34059402
17800000	-53.33984648
17900000	-53.33911147
18000000	-53.33838871
18100000	-53.33767793
18200000	-53.33697886
18300000	-53.33629125
18400000	-53.33561486
18500000	-53.33494943

Frequency Hz	Attenuation dB
18600000	-53.33429473
18700000	-53.33365054
18800000	-53.33301663
18900000	-53.33239277
19000000	-53.33177877
19100000	-53.33117441
19200000	-53.33057949
19300000	-53.32999381
19400000	-53.32941719
19500000	-53.32884944
19600000	-53.32829038
19700000	-53.32773984
19800000	-53.32719763
19900000	-53.32666359
20000000	-53.32613756
20100000	-53.32561938
20200000	-53.3251089
20300000	-53.32460595
20400000	-53.32411041
20500000	-53.32362211
20600000	-53.32314092
20700000	-53.3226667
20800000	-53.32219932
20900000	-53.32173864
21000000	-53.32128455
21100000	-53.32083691
21200000	-53.3203956
21300000	-53.31996051
21400000	-53.31953151
21500000	-53.31910849
21600000	-53.31869135
21700000	-53.31827998
21800000	-53.31787426
21900000	-53.3174741
22000000	-53.31707939
22100000	-53.31669004
22200000	-53.31630595
22300000	-53.31592702
22400000	-53.31555317
22500000	-53.3151843
22600000	-53.31482032
22700000	-53.31446115
22800000	-53.31410671
22900000	-53.3137569
23000000	-53.31341166
23100000	-53.3130709
23200000	-53.31273454
23300000	-53.31240251
23400000	-53.31207474
23500000	-53.31175115
23600000	-53.31143167

Frequency Hz	Attenuation dB
23700000	-53.31111623
23800000	-53.31080476
23900000	-53.31049721
24000000	-53.31019349
24100000	-53.30989356
24200000	-53.30959734
24300000	-53.30930477
24400000	-53.30901581
24500000	-53.30873037
24600000	-53.30844842
24700000	-53.30816989
24800000	-53.30789473
24900000	-53.30762288
25000000	-53.30735429
25100000	-53.30708891
25200000	-53.30682668
25300000	-53.30656757
25400000	-53.30631151
25500000	-53.30605847
25600000	-53.30580838
25700000	-53.30556122
25800000	-53.30531693
25900000	-53.30507546
26000000	-53.30483678
26100000	-53.30460084
26200000	-53.30436761
26300000	-53.30413703
26400000	-53.30390907
26500000	-53.30368368
26600000	-53.30346084
26700000	-53.3032405
26800000	-53.30302263
26900000	-53.30280719
27000000	-53.30259413
27100000	-53.30238344
27200000	-53.30217506
27300000	-53.30196898
27400000	-53.30176515
27500000	-53.30156354
27600000	-53.30136412
27700000	-53.30116686
27800000	-53.30097173
27900000	-53.3007787
28000000	-53.30058773
28100000	-53.3003988
28200000	-53.30021187
28300000	-53.30002693
28400000	-53.29984394
28500000	-53.29966288
28600000	-53.29948371
28700000	-53.29930642

Frequency Hz		Attenuation dB
28800000		-53.29913097
28900000		-53.29895734
29000000		-53.2987855
29100000		-53.29861544
29200000		-53.29844712
29300000		-53.29828053
29400000		-53.29811563
29500000		-53.29795241
29600000		-53.29779084
29700000		-53.29763091
29800000		-53.29747258
29900000		-53.29731584
30000000		-53.29716066

Frequency Hz		Attenuation dB

Frequency Hz		Attenuation dB

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